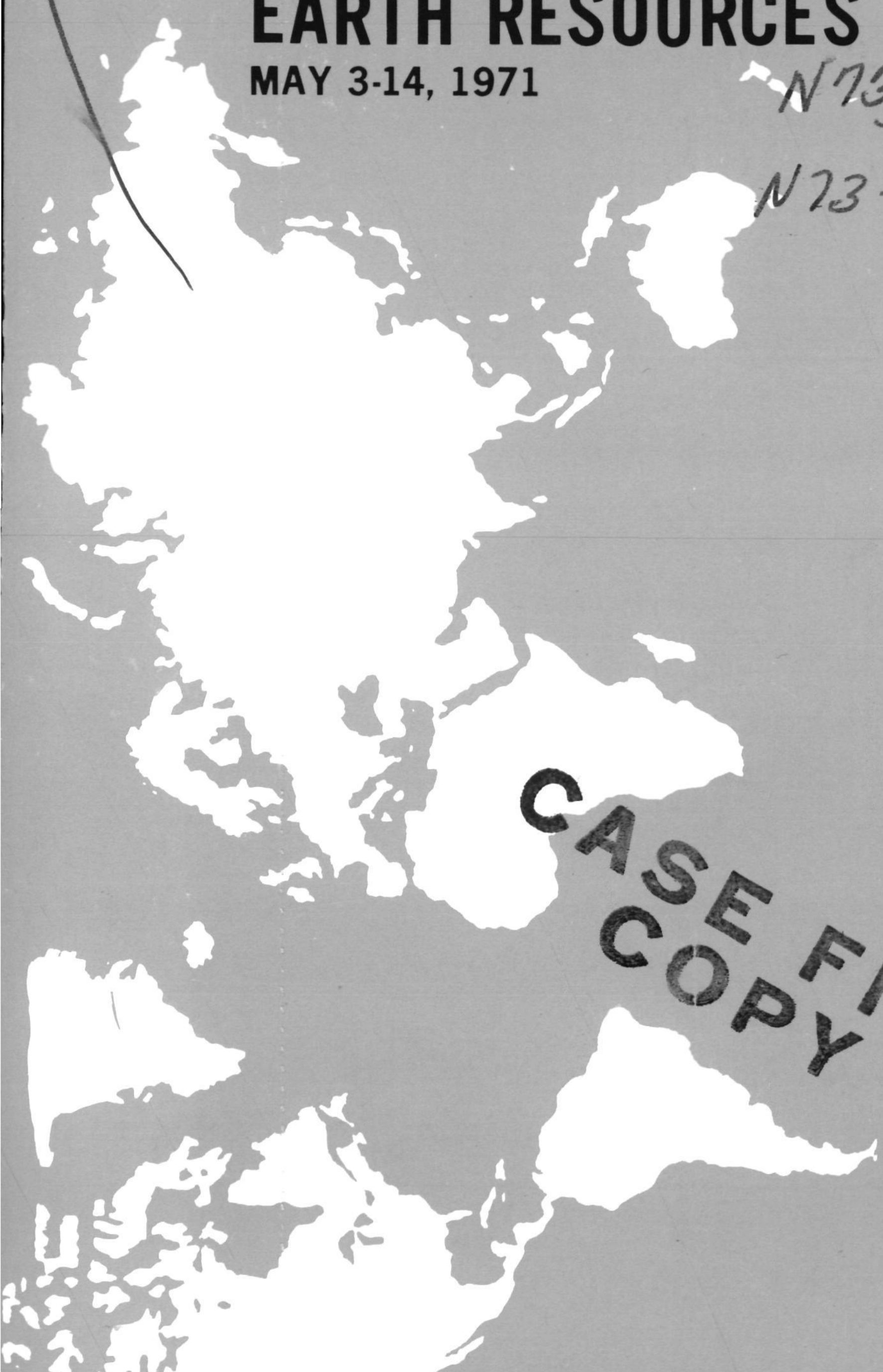
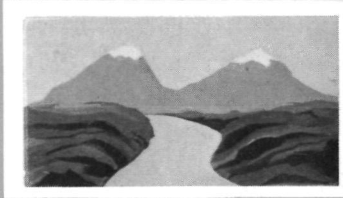
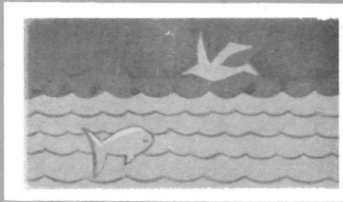
INTERNATIONAL WORKSHOP ON

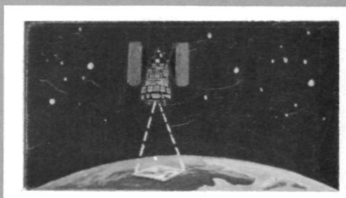
EARTH RESOURCES SURVEY SYSTEMS

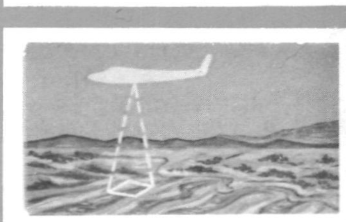
MAY 3-14, 1971











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Volume I

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EARTH RESOURCES

SURVEY SYSTEMS

Volume I

Proceedings of an international workshop held at the University of Michigan on May 3–14, 1971, and sponsored by the National Aeronautics and Space Administration, the Department of Agriculture, the Department of the Interior, the National Oceanic and Atmospheric Administration of the Department of Commerce, the Naval Oceanographic Office, the Agency for International Development, and the Department of State

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Preface

In a statement before the United Nations General Assembly on September 18, 1969, President Nixon said, "Of all of man's great enterprises, none lends itself more logically or more compellingly to international cooperation than the venture into space. . . . we are just beginning to comprehend the benefits that space technology can yield here on earth. And the potential is enormous. . . . I feel it is only right that we should share both the adventures and the benefits of space. As an example of our plans, we have determined to take actions with regard to earth resource satellites as this program proceeds and fulfills its promise. The purpose of those actions is that this program will be dedicated to produce information not only for the United States but also for the world community."

As one of the actions foreseen in the President's message, the U.S. representative at the September 1, 1970, meeting of the United Nations Committee on the Peaceful Uses of Outer Space announced that the U.S. would hold an International Workshop on Earth Resources Survey Systems. This workshop has been organized to describe the Earth Resources Survey Program of the U.S., its content, techniques and results to date, and its future plans. The potential contribution of remote sensing data to the solution of resource problems and the experimental material which is expected to become available to other countries are also discussed. The workshop also provided a forum in which other countries described their own related programs.

This volume of the proceedings contains the speeches and papers presented during the sessions of the first week of the workshop (May 3–7, 1971).

At the request of delegates attending the second week of the workshop, color transparencies (35 mm) of all of the lecture slides for both the first and second weeks are being furnished to the heads of the delegations of each country represented at the workshop. Therefore, this volume of the proceedings is printed with black-and-white illustrations similar to Volume 2.

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Chairman's Introduction

HOMER E. NEWELL

Associate Administrator
National Aeronautics and Space Administration

Our purpose here is to bring together in one spot, for a period long enough to be meaningful, some experts in the new remote sensing technology that is being developed and some of those throughout the world who are interested in the application of this technology to the direct benefit of humanity. The latter category includes both technicians and those in the various countries who may be responsible for planning, programing, and funding remote sensing projects. We hope to achieve a practical exchange of information in order to establish a basis for further development and application of this promising new technology in the developing and developed countries alike.

During the course of the workshop, you will hear about the application of remote sensing to resource problems. You will hear about the U.S. Earth Resources Technology Satellites, which will be referred to as ERTS-A and ERTS-B, and the Earth Resources Experiment Package (EREP), which the National Aeronautics and Space Administration (NASA) expects to launch starting in 1972. You will also hear about aircraft remote sensing systems, the ground data handling systems which are a very important element of the overall effort, and the essential ground survey activities. It will indeed be a considerable task to cover all this material in a two-week period.

The afternoon session on Wednesday, May 5, will be devoted to sessions on the economic bases for making decisions to invest in resource surveys and on cost benefit analyses and decision models. On Thursday, representatives of six other nations will describe their remote sensing programs. On Saturday morning, you will have an opportunity to visit the remote sensing aircraft of NASA and those of the University of Michigan at the Willow Run Airport.

I would like to call your attention to the fact that the University of Michigan is sponsoring the Seventh International Symposium on Remote Sensing of the Environment from May 17 to 21, immediately following the workshop. The symposium will be held in this same auditorium. The workshop and the symposium are complementary in that papers will be presented at the symposium on the latest research results by scientists participating in the program. We encourage all those who can remain to attend the symposium.

During the first week of the workshop, there will be simultaneous interpretation into French and Spanish. As indicated in the announcement for the workshop, we will not be able to do this for the second week, since there will be no plenary sessions such as this. Instead, the delegates will divide into small workshop sessions to work on the application of remote sensing data to specific resource problems.

You may be interested in knowing what countries and international organizations have sent representatives here to the workshop. The list of participants shows that 39 countries and 15 international organizations have responded to the invitation to send representatives. This gives a total of 54 countries and international organizations. I understand that about 350 persons have indicated their intention to attend. A complete list of registrants will be available by the middle of the week. We hope you will all enjoy and profit from this workshop.

We are very pleased to have with us today Representative Larry Winn of the House Committee on Science and Astronautics of the U.S. Congress.

It is my pleasure now to introduce the United States Ambassador to the United Nations, the Honorable George Bush, who will make the official welcoming address on behalf of the United States. Ambassador Bush has had an extensive career in business, which has taken him to countries all around the world. He served in the U.S. Congress as Representative from Texas and, there, was a member of the House Ways and Means Committee. This background gives Ambassador Bush an unusual understanding of the importance of the subject of this conference. In addition, from his position as Ambassador of the United Nations, Ambassador Bush has a special concern with the international aspects of the subject. I am pleased to present Ambassador George Bush to make our official welcoming address.

PARTICIPANTS IN INTERNATIONAL WORKSHOP

Countries (39):

Argentina	India	Philippines
Australia	Indonesia	Portugal
Belgium	Iran	South Africa
Bolivia	Israel	Spain
Brazil	Italy	Sudan
Canada	Jamaica	Sweden
Chile	Japan	Switzerland
Colombia	Lybia	Thailand
Finland	Mexico	Turkey
France	Netherlands	Uganda
Germany	Pakistan	United Kingdom
Ghana	Panama	Venezuela
Greece	Peru	USSR

International Organizations (15):

United Nations
UNESCO (UN Educational, Scientific and Cultural Organization)
ITU (International Telecommunications Union)
FAO (Food and Agriculture Organization)
ECAFE (Economic Commission for Asia and the Far East)
ECLA (Economic Commission for Latin America)
WMO (World Meteorological Organization)
Asian Development Bank
ESRO (European Space Research Organization)
COSPAR (Committee on Space Research)
OAS (Organization of American States)
PAIGH (Pan American Institute of Geography and History)
PAHO (Pan American Health Organization)
IBRD (International Bank for Reconstruction and Development)
Euratom

Total: 54

Welcoming Address

GEORGE BUSH
United States Ambassador to the United Nations

First of all, I would like to read the following message from President Nixon to this international workshop:

"It was nearly two years ago that the television cameras of Apollo 11 gave us all the opportunity to share in the adventure of man's first step on the Moon. Two months later, in September of 1969, I confirmed to the General Assembly of the United Nations that the United States would continue to share with the world community both the adventures and benefits of space research, including those of the Earth Resources Satellite program. I greet you today with the wish that this International Workshop on Earth Resources Survey Systems will help this new technology come into its own in the service of mankind."

I suppose nothing could underscore the importance with which the entire United States Government views this workshop more than that message from President Nixon. The complexity, the promise, and the hope of this new technology are further dramatized by the unprecedented sponsorship of this gathering by United States departments and agencies with interests as diverse as the National Aeronautics and Space Administration and the Departments of the Navy, Agriculture, Interior, Commerce, the Agency for International Development and, of course, the State Department.

This workshop is here to talk about a very special, exciting, challenging, and as yet experimental technology which offers brilliant promise for virtually all mankind. It is of real and symbolic importance that with us today and participating in the first week of this workshop we have some 30 members of the United Nations Panel on Remote Sensing Systems for Earth Resources Survey. The presence of this group, along with all of our workshop participants from nations around the world and from international organizations and United Nations Specialized Agencies, is a manifestation of President Nixon's pledge to share the benefits of space in the service of mankind.

As many of you probably know, I am pretty new at this job, but I already know all too well how often the United Nations is criticized here in the United States and elsewhere for being unable or unwilling to solve all the problems that beset our troubled planet. It is a pleasure, then, to speak on a topic which has been a concern of the United Nations for more than a decade and which, by and large, has been an area marked from the beginning by international cooperation. The UN panel here with us today is but one of several invited to visit countries which have programs to apply space technology to economic and social problems in search of practical solutions. These panels will report their findings back to individual UN member states and specialized agencies.

It is important to note that, when we speak of applying space technology to practical problems, we are not speaking just of the transfer of technology or information from an advanced space power such as the United States. Other countries have invited UN panels to come and observe their experiments and their programs. These countries include Brazil and India. Thus we see early but hopeful signs that many countries, regardless of their overall state of economic or technological development, are prepared to share their own experience with others seeking assistance.

Basically, of course, space technology is a global tool, and for a global tool to be used productively and efficiently there must be a climate of international cooperation. We are not doing badly. Satellites now speed telephone, radio, and television communications around the world in moments. More than 70 countries have Automatic Picture Transmission (APT) sets to receive data directly from weather satellites. In the not-too-distant future we should see the first experimental educational satellite placed in orbit. As our technology improves, our applications of satellites should become increasingly diverse and the process of development should accelerate.

One of the roles which this workshop and the United Nations panel can help play is to provide policy makers and program managers in developing countries with the basic information to enable them to consider seriously how this new technology may help them meet their needs. Starting with the Conference on the Applications of Space Technology in Vienna in 1968, the United Nations, through the Committee on the Peaceful Uses of Outer Space, has been increasingly concerned with this problem.

I am proud of the role which my own government has played in the Outer Space Committee itself and in supporting the various efforts within the United Nations to speed the exchange of information and find more and increasingly varied applications of space technology for the benefit of all. To this end, President Nixon, a little over a year ago, included in his statement of objectives of the U.S. Space Program, hastening and expanding the practical applications of space technology, working to reduce the cost of that technology and thus to make it increasingly accessible and useful to all countries, and, of course, as is evident by our meeting today, encouraging greater international cooperation in space.

The UN has been an important element in fulfilling U.S. objectives to expand our cooperation in space activities. Through the UN and bilateral contacts we solicited proposals for participating in experiments connected with the Earth Resources Technology Satellites. You might be interested to know that 26 countries have submitted some 60 proposals for participation. In January 1970 members of the outer space committee and key UN Secretariat officials were briefed on the Earth resources program at the Manned Spacecraft Center in my hometown, Houston, Texas. We also have submitted a detailed working paper on Earth resources to the Scientific and Technical Subcommittee of the Outer Space Committee. Finally, in conjunction with the UN, we are establishing a fellowship program to provide training for specialists in selected fields relating to the application of space technology.

When President Nixon spoke to the General Assembly in 1969, he said, "I feel it is only right that we should share both the adventures and the benefits of space." Well, man has shared many of the adventures of space. A little noticed phrase in the two treaties pertaining to outer space which have emerged from the United Nations refers to those who venture into the void as "the envoys of mankind." That is not only an elegant phrase, it is a poignant and magnificent statement of the complex of emotions ranging from pride through fear and awe and humility which I think all of us have felt whenever we have known that one of our fellow men was circling this planet or looking down on or walking on the Moon. But sharing the benefits of space can also be an adventure, and that is what this meeting is all about. We are here embarking on a voyage on which each of us is also an envoy of mankind. And with luck, diligence, and a continued sense of sharing and cooperation we will all live to see the day on which this faint glimmer of technological promise becomes a sunburst of fulfillment which will improve beyond man's wildest dreams the quality of his life and the quantity of what he needs to sustain and improve his life.

I'm afraid I'm a layman in this field of technology, but that makes me no less concerned about the future of meetings such as this one, the efforts of the UN Outer Space Committee, and the myriad programs for sharing and transferring technology of all types among the nations of our world. From my new vantage point at the United States Mission to the United Nations, I will enthusiastically assist in every way I can in the fulfillment of the pledge which my Government has made to make available for mankind the benefits of this exciting technology.

The Earth From Space

WILLIAM A. ANDERS

Executive Secretary
National Aeronautics and Space Council

I am pleased to be with you today as part of your workshop and to have a chance to speak to you about this very important program on which you are embarking. Ambassador Bush and I are from the same hometown, Houston, Texas; and I can remember not too long ago when many of us, many of you here in this room, went to Houston to view the very interesting and developing capabilities in Earth resources survey.

I believe that the purposes which have brought us all here together are ones which reflect the highest qualities of human endeavor. Taking a broad view of the goals of this meeting, we are attempting to learn how to use the most advanced products of man's intelligence and coordinated effort—that is, aerospace technology—to solve some of the many problems that face society and our planet.

I am happy to be here, however, not only because I strongly support the purposes of this workshop, but also because I believe that I have a few observations to make to you which are pertinent to its subject, the Earth Resources Survey Program. My views on this program have developed partially as a result of the position I now hold in Washington but more particularly because of my former career as an American astronaut.

The Earth Resources Survey Program is one of the key elements of the United States space program of the 70's. I firmly believe that the full purpose of this program can be achieved only if it is carried out not just as an American program but as a joint international enterprise, with early and active participation by all interested nations. This participation must include defining the program, interpreting the data it produces, and applying the results and information to the needs of your own people.

My experiences during the Apollo program left some strong and lasting impressions upon me, impressions which are related directly to my views on the importance of Earth resource survey. I was fortunate to be one of the first three, as Ambassador Bush and our President said, "envoys of mankind." To leave the influence of our home planet and view our Earth from afar, to make the voyage from Earth to the Moon and back is an experience which profoundly influences all those who have undergone it; and I am no exception.

The Moon is a very interesting place scientifically, a very important place, one where we are learning not only about our nearest neighbor in the universe, but also about the origin and structure of our home planet. But, although the Moon is very impressive, the most impressive sight for me on that flight was the view of the Earth itself. From the Moon, the Earth appeared as a small, blue-green sphere, like a beautiful, fragile Christmas tree ornament I could cover with my thumb by holding it out at arm's length—very delicate and limited, the only color in the whole universe, the only friendly place we could see. Certainly the ancestral home of mankind did not appear vast, unlimited, and indestructible as we often see it when groping here on its surface. It seemed much more like the delicate and fragile Christmas tree ornament that you must learn to preserve and protect with appropriate care.

Looking back, I saw no national boundaries, no dividing up of the Earth into separate States, each with a different color, as you see on a globe in a

school classroom, a globe divided on the surface by man but obviously not by nature when viewed from this perspective. I saw instead a small but inviting oasis in the vast blackness of space. Perhaps the American poet and playwright Archibald MacLeish best summed up the feeling I had when viewing the home planet from nearly a quarter of a million miles away when he wrote of seeing "the Earth as it truly is, small and blue and beautiful in that eternal silence where it floats," a view which leads us "to see ourselves as riders on the Earth together. . . ."

I believe that historians will record that one of the most profound impacts of man's exploration of outer space is the change it is producing in the way we think about the planet on which we live. Apparently we've had to leave this planet, either in reality as I did or vicariously through television and photographs, to see the Earth as it really is, as a whole: a single, small, fragile outpost in the universe in which billions of human beings have a stake. In this sense, the true physical unity of our spaceship Earth may be the most lasting impression resulting from our trips to space. It's the impression that I want most to reinforce with you this morning as you begin your very important work. If the planet is indeed an interrelated whole, then effective use and conservation of its finite resources can best be achieved by a global approach, an approach which obviously must have international participation.

The program we've gathered here to discuss, the Earth Resources Survey Program, is a means of obtaining that overall view of the Earth's land, water, and air masses. Such a view is essential if we're going to develop means of successfully managing these resources for the benefit of all mankind. It seems to me that the Earth Resources Survey Program will provide much of the information that we need to help achieve the delicate balance between the efficient use of the Earth's potentials and their misuse. Without such a program, we would be forced to make resource decisions in the future as we too often have had to do in the past—without adequate knowledge or assessment of the overall implications. Wrong decisions or poor decisions due to inadequate data will affect not only the perpetrator but others elsewhere as well. The value of the resources of our planet and their husbanding are not a narrow or even a national concern, but are truly global in extent.

In one sense our major space enterprise of the 60's, Project Apollo, was a direct response to a challenge presented in 1958. The Soviet Union, the Sputnik, gave us something really to work toward. Though the NASA program grew and received national support as a reaction to the first Sputnik, the direction and intensity of the effort were determined by a particular aspect or facet of the American spirit. Not that this fact is surprising, for every country stamps the shape of its undertakings with the spirit of its people. In the United States, the dominant spirit has been one of exploration and the pioneering of new frontiers. This spirit is due, many say, to the fresh memories of the opening up of our own country. Moving into new lands and helping and sharing with one's neighbors are really part of the American heritage. Our pioneering urge, when applied to space, has taken us onto two roads. One is scientific and encompasses astronomy, planetary observations, solar physics, and the like; the other, and by far the larger undertaking, was lifting man into space to test his abilities and endurance, to use his intelligence and discretion and, finally, to send him to an unknown and strange place, where, in the tradition of other explorers, he brought the footprint of man and the eye of a trained observer.

Now what about the United States space program of the 70's? How will it differ from what went before? How does the pioneering urge of the American fit into the space challenge of the decade before us? For one thing, international space competition, while real, is no longer the driving force influencing our policy as it once was. We no longer have to demonstrate our capability to operate in all regions of space; that has been done—and convincingly. We now have to decide how to employ that capability and still combine new challenge and immediate benefits—not just for our country but for all men on Earth.

One of the most influential factors in our current space policy is the remarkable discovery, which was very clear to me on my Apollo mission, that the most interesting thing to explore in space is not the Moon, or Mars, or some far off galaxy, but our own planet. Accordingly, our plan for the 70's is to develop a balanced United States space program,

one aimed at three objectives: the basic drive of America toward continued exploration, a continued acquisition of new scientific knowledge, and an increase in the practical benefits to mankind. It seems to me that the Earth Resources Survey Program embodies all of these objectives. I believe it will be one of our most important and stimulating undertakings in space in the coming years.

The Earth Resources Survey Program will employ the best of the capabilities we have developed. Not only will we launch an unmanned Earth resource survey satellite next year, but astronaut crews on a Skylab space station will, as an important part of their activities, conduct a series of experiments aimed at assessing the particular contributions man can make in conducting resource surveys from space. Hopefully we can have international crews of scientists working on such projects in the future. The benefits of an Earth resource program, most agree, are likely to be tangible, large, and broadly relevant. Not only will the program have tangible benefits, but it will also have strong elements of global scope and exciting challenge to energize our best efforts. This program should not, indeed cannot, be only an American undertaking, however. The maximum benefits of the program will be obtained only if surveys are conducted and results used on a global basis. Our President and those who are planning the United States program are well aware of this reality. This workshop is only one manifestation of this fact. I think our policy on this quest has been farsighted and well articulated.

President Nixon has recognized that our space program should not be based on unilateral U.S. action. He has pledged to increase international participation in our space efforts and, particularly and immediately, in Earth resource survey. The President told the United Nations in 1969, as Ambassador Bush indicated, that this program will be dedicated to producing information not only for the United States but for the world community; and that's why we meet here today.

In a sense, we view the United States Earth Resources Survey Program as an offer to the rest of the world, an offer of the most advanced of our developments to be used for the most crucial of needs. But we cannot, by ourselves, design or carry out such a program. We cannot know in precise detail the needs of each country in the world, nor can we know how to interpret the data we gather in order to make it most useful in meeting those needs. These are difficult tasks that require the cooperation of all those interested in a joint endeavor, which this technological capability makes possible.

It would not be realistic to talk to you this morning only of the promise of the Earth Resources Survey Program without also talking about some of the present limitations on obtaining very immediate large-scale benefits from it. I'm sure you'll be cautioned at this workshop about the experimental nature of the current United States Earth resource survey effort. I shall not dwell upon this point, but you must be aware that we are just at the start of something which will have some short-term benefits but will have immeasurably more benefits and applications in the second half of this decade and beyond, as we move from experimental to operational stages. Of course, we must learn to work together now if this forecast is to be true. This workshop, I hope, will provide the forum in which we can gain both a realistic appreciation of the potential benefits of the Earth resource program and an assessment of what is needed to translate this potential into a reality. In closing, let me say that there is, at least in my mind, a steady progression from the views of our planet brought back by those of us who have left its friendly vicinity and were able to observe its uniqueness from a new perspective, to the concept of surveying the Earth's resources from space. This progression is one which can result in significant benefits for all men if we learn to live and work together. I'm proud that my mission, Apollo 8, was a link in this progression.

I would like to close my remarks with a comment made by Richard Nixon, then President-elect, at the end of the Apollo 8 mission, when he said: "In that moment of surpassing technological triumph, men turn their thoughts toward home and humanity, seeing in that far perspective that man's destiny on Earth is not divisible, telling us that, however far we reach into the cosmos, our destiny lies not in the stars but on the Earth itself, in our own hands and in our own hearts." By working together with a new awareness of our planet and of ourselves, by using the new tools now at our disposal, we can make this planet truly a beautiful place to live for all mankind, as it appeared to me from Apollo 8 on Christmas of 1968.

A Lofty View of the World Around Us

W. T. PECORA
Director
U.S. Geological Survey

Somewhere in the distant ages of prehistoric time, primitive man sensed the importance of communication, developed a rudimentary technology, and learned to cooperate with his fellow men in solving problems. This enlightenment made it possible for humans collectively to cope with the great adversities that otherwise might have overwhelmed them.

The discovery that fire could be made at will, the development of primitive agrarian cultures, and the construction of dwellings in the interest of protection and efficiency stand as typical milestones in man's steady upward climb to the technical societies of today. Looking backward in time, one can see that we have populated the entire planet in the short span of a few thousand years; we have explored its heights and depths to a considerable degree; and we even have walked on another world.

Now, as we marvel at these remarkable accomplishments, we are faced with the sobering realization that the world in which we live is finite. Indeed, it is a solar island from which there is no permanent escape, whatever our aspirations or illusions may be. The lives we hope to lead must be lived here, within the limits of the Earth's surface and within the limits of its natural resources.

MAPPING

How well do we know the surface of the Earth? The answer is: "Not well enough!" A fair measure of man's knowledge is in the number, kinds, and accuracy of the maps he makes. How well are we doing with mapping? A recent U.N. study shows that only about 6 percent of the land surface of the world is covered by topographic maps at a scale of 1:60 000 or larger.

Maps are needed now more than ever to maintain a current reliable inventory of the physical factors that affect the air we breathe, the water we drink, the lands and forests we cultivate, the mineral resources we mine, the industries we operate, the arteries we use for transportation and communication, and the communities we live in. Without maps upon which to inventory the nature, content, and use of the Earth's surface, our efforts to use the environment effectively for the benefit of all mankind are severely handicapped.

HUMAN NEEDS

Assessment of human needs is vastly different today than it was in primitive cultures when the energy requirement of each person was only 0.36 megajoule per day. Today's highly industrial societies expend 100 times this amount of energy per person in providing the supplies, facilities, and services to which we have grown accustomed. Only a century and a half ago man was concerned with obtaining fewer than a score of chemical elements to survive and to support his industries. Today he must locate mineral sources for more than 80 chemical elements just to maintain a modern way of life.

Coupled with these spiraling energy and mineral requirements is the hard fact that the number of people who hope for the better living standards is growing day by day. To put this trend in perspective, the world's population of 3.5 billion now is

increasing at a rate which is expected to double the number of people every 35 years, and there is some evidence that this rate may double in certain parts of the world before the turn of the century. The present rate of expansion produces a new increment of population equal to that of Ann Arbor, Michigan, in a half day, and will yield a world population of 30 billions of people within a century.

MINERALS

In much of the world, the rate of energy consumption is growing twice as rapidly as the population. This additional energy is being consumed in processing the ever-increasing quantities of raw materials needed, to accommodate demands which undoubtedly will continue to grow, even if the population is stabilized or its growth rate is reversed. In the United States alone, the demand for primary ore minerals is expected to expand fourfold by the turn of the century. This will mean, for example, that we must produce 7.5 billion tons of iron ore, 1.5 billion tons of aluminum ore, 1 billion tons of phosphate ore, and 100 000 tons of copper metal by the year 2000. Incorporated in this growth will be the need for a long list of mineral "vitamins," such as cobalt, tungsten, vanadium, and mercury, which are in short supply and widely scattered over the Earth's surface.

One could relate similar statistics for the needs of people throughout the world. The difficulty in meeting them will be compounded by the fact that only a fraction of one percent of the Earth's surface yields readily available high-grade ore, most of the mineral wealth being hidden beneath the surface and not readily detectable. Furthermore, the difficulty and cost of locating and producing the minerals we need will continue to increase as the grade of the ore decreases.

WATER

Water is an exceptionally critical resource that must be reckoned with in the days to come. Not only must water serve as a raw material, a process fluid, and a waste carrier for our industries, but it must also sustain agricultural operations on which we depend for food supplies. Water also plays a significant role in our transportation and recreational activities.

It is troublesome that much of the water on this planet is not in the right place, or of the proper quality, for the use we would like to make of it. Characteristically, civilizations have searched out and clustered around the best available water supplies. As growing numbers pressure us to occupy less favorable semiarid regions and desert areas, better exploratory systems must be devised for locating whatever water resources are available and for monitoring undesirable effects on the waters we use.

Projections of water needs in this country illustrate the importance of obtaining more and better water data. Ten years ago, per capita water use was about 1500 gallons per day. By the year 2000, with a probable population of about 350 million, each person will in effect be using 2500 gallons instead of 1500 gallons per day. The product of these trends could result in our using as much as 75 percent of the total average runoff from the Nation's rivers. And the problem is further compounded by the clustering of people into huge megalopolitan areas.

Intense exploration with sophisticated techniques will be required to seek out every substantial underground water reserve which might help meet this growing demand, and much better systems of surveillance will be needed to insure that adequate standards of quality are maintained.

FOOD

The task of supplying food for increasing numbers of people involves several important subordinate steps. We must first seek out the productive lands and then guide human use in a manner that will preserve as much agricultural productivity as possible. The Earth's environment then should be monitored for clues to troublesome effects of exotic nutrients and pest controls, and for sounding the alarm on troublesome reactions to the activities of man, such as the encroachment of salt water into soils.

The ability of future populations to survive on the planet will depend in large part on the effectiveness with which such information can be gathered. As pointed out by Ellsaesser in the March 1971 issue of EOS Transactions of the American Geophysical Union, one can find estimates that an eightfold increase in current agricultural production is the maximum we can expect. This assumes a

doubling of the Earth's agricultural land area and a fourfold increase in its productivity. Because this marked increase will be needed simply to keep pace with the population growth expected by 1975, it is obvious that the need for better land-use inventories and crop surveillance systems is a critical one.

PLANNING

As people cover more and more of the Earth's surface, it will not be enough to seek out the mineral resources needed to sustain them, or even to supply them with adequate amounts of food and water. It also will be necessary to keep close watch on urban growth and to warn in advance of patterns which may have undesirable consequences. The watchful eye of the land-use planner must insure, as far as practicable, that urban growth does not create impossible water supply problems; that urban expansion does not preempt important agricultural land and mineral deposits, nor defile natural wonders; that urban development does not set the stage for natural disasters such as landslides, earthquakes, and floods; and that urban sprawl does not create unnecessarily troublesome transportation, communication, or pollution problems.

There is little doubt that the present urban growth rate is outdistancing the periodic censuses and the conventional explorations of Earth resources which have guided urban development in the past. Modern planners and managers are clamoring for more timely environmental data and better interpretation of it in terms of the decisions they must make.

NEW TOOLS

The ability to devise and use new tools has been a basic element in the uniqueness of man from the very beginning. As we look to the many problems of the future, it is logical to ask what tools will be needed to do the job. Will the present ones suffice, or must we devise more sophisticated ones to supplement our present capability? When the Earth's resources were relatively abundant in comparison with human needs, the conventional techniques of prospecting served us well. No tool of the future is likely to replace them completely, as far as final confirmation and critical evaluation are concerned. But it is clear that they must be augmented by new and more efficient methods to meet the needs of the future.

REMOTE SENSING

Necessity during the last quarter century has mothered the invention of a variety of first-generation remote sensing systems for rapid scanning of the Earth's features and resources. These systems have served as excellent supplements to conventional investigations. Modern photographic and photogrammetric techniques for precise surface mapping, magnetic and gravity surveys of hidden Earth structures, electric logging of exploratory drill holes, and special airborne sensors, such as the mercury analyzer, are all products of this first effort to provide more and better information in less time about the Earth on which we live.

The early successes in remote sensing have encouraged the search for new tools which lend themselves to more lofty viewpoints, wider coverage, and faster monitoring. Satellite programs of the past decade provided vehicles for such systems and set the stage for the entrance of a new generation of sensors. When Earth resource satellite systems now on the drawing board are perfected, man will be able to scan a wide swath of the Earth's surface with a great variety of sensing devices and within a very short time frame. Such scanning will provide a new and useful perspective of the Earth, one which will allow us to stand back and examine pertinent features of the whole picture instead of its minute details. For the first time, we will be able to study the forest instead of the trees.

SATELLITES

A particular advantage of satellite observations is that they can be repeated frequently enough under identical lighting conditions to yield a record free of the aberrations which have troubled conventional aerial studies. Gross geologic structures, evidence of health or sickness in forests and food crops, soil types, land-use patterns, telltale marks of oil seeps, evidence of ground water, pollution scars on the environment, and trends in urban sprawl are features that we will eventually be able to spot from a lofty platform.

When fully developed, an Earth resources satellite system could provide a continuing inventory of surface waters and snow packs throughout the world, provide useful information on the abundance or deficiency of global food supplies, and keep a watch-

ful eye on the weather which alternately favors or threatens our present way of life. The uses which might be made of such a system will be limited only by the resourcefulness of the investigator.

The prospect of developing new remote sensing tools embodied in the resource satellite system is an exciting one, to be sure, but it would be foolish to assume that development of maximum capability will be a quick or easy task. It would be equally foolish to assume that remote sensing ever will replace traditional Earth survey techniques. Images received from orbit, like those of the first electron microscope, will present the investigator with new and tantalizing information. They will present relatively exotic pictures of the world in which we live, pictures packed with hidden facts that must be interpreted through intensive study. One can expect that each new discovery of meaningful information will suggest other uses which remote sensing can serve.

COOPERATION

The task of developing the full potential of new monitoring systems is not the responsibility of a select group of scientists, nor of a particular nation. It is the task of everyone with initiative, resourcefulness, and a genuine interest in the world around us.

Each anniversary of an international cooperative effort of this kind will see new and valuable technical information to report concerning accomplishments in the Earth resources survey satellite program. And there will be social benefits, as well, that will evolve from a better understanding of each other's problems.

I am certain that this international workshop, the first of its kind, will be immensely effective in determining how we can live in reasonable harmony on the planet Earth. I want to congratulate those of the National Aeronautics and Space Administration as well as those in the Department of Agriculture, the Department of the Interior, the National Oceanic and Atmospheric Administration of the Department of Commerce, the Naval Oceanographic Office, the Agency for International Development, and the Department of State who have worked so hard to make this workshop a reality.

In the next few days you will learn about the numerous accomplishments that have already come from Earth resource survey experimental programs. You will hear about exciting plans for the future. The launching of NASA's ERTS satellite in March 1972 will mark the beginning of a new era of space applications for the benefit of mankind. Collectively we can maximize these benefits.

With this as our goal, the workshop will certainly be a profitable and rewarding experience for all of us. I wish you much success.

The Earth Resources Survey Program

LEONARD JAFFE

Deputy Associate Administrator for Space Science and Applications, NASA

The possibility of surveying Earth resources from orbital altitudes was recognized during the early days of our space program, based on observations from meteorological satellites and photography from manned missions such as the Mercury and Gemini. A couple of examples are shown in figures 1 and 2. Before discussing the program, we shall define remote sensing and a few of the terms that are peculiar to this area of technology.

BASIS FOR MULTISPECTRAL REMOTE SENSING

Remote sensing refers to an ability to sense or detect electromagnetic radiation which emanates from an object. Every object emits (radiates) and reflects electromagnetic energy. We are most familiar with light waves. Our eyes sense remotely the existence of, and permit identification of, objects because these objects emit or reflect light waves, which are a form of electromagnetic energy. We can identify or interpret what we see remotely because our eyes construct an image of the object. The object's shape and texture help tell us what it is. The color or spectral content of the object's emitted and reflected radiation also help us to identify the material that we are looking at. A knowledge of these characteristics usually permits a unique identification of the object itself or at least the materials from which the object is made.

Electromagnetic radiations can occur over a wide range of frequencies or wavelengths. The human eye responds to only a very small portion of the electromatic spectrum, which includes wavelengths much shorter and much longer than those of visible light.

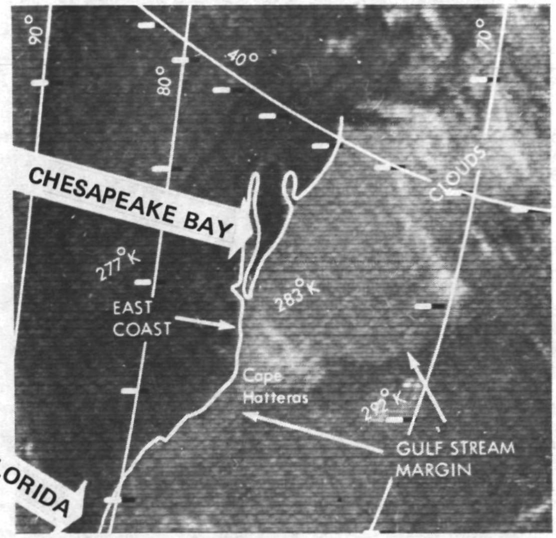


FIGURE 1. Nimbus II high-resolution infrared imagery clearly depicts the Gulf Stream. Temperature values were determined by microdensitometer.

An imager is a device which, like the human eye, produces a two-dimensional view of a scene being observed. A camera is a type of imager. Another type is described below.

A radiometer is a device which measures the amount of electromagnetic energy emitted from a given area of a scene. A radiometer that is sensitive to a number of different frequencies and can record the energy radiated at different frequencies by the scene is called a spectrometer.

If one moves a radiometer or spectrometer (which at any time sees only one spot) over the entire scene and records the measurements while systematically scanning the scene, one can construct an image of

FIGURE 2. Vertical view of the Florida Keys with the Everglades National Park and Cape Sable visible at the top of the photograph. The shoal areas and underwater detail from Key Largo to Boca Chica Key are seen in the center. The structure in the pattern of Sun glitter on the water (whitish area) is partially due to slicks.

the scene. A device used in this way is called a scanning radiometer, a scanning spectrometer, or sometimes a scanner for short. A unique pattern of frequencies or wavelengths radiated by an object is called the spectral signature of the object.

There are a number of advantages to be gained by utilizing various portions of the spectrum in addition to the visible. To begin with, some features will appear clearly at one frequency, but will not be discernible at another. Simultaneous images in various spectral bands may be compared, making it possible to discriminate between features or phenomena which exhibit no apparent differences in the visible range alone. Images from one spectral region may also be combined with those from another spectral region, and a single composite image can thus be obtained representing an optimum "picture" for certain analytical purposes. This technique is called multispectral sensing.

Secondly, new types of information not obtain-

able from visible data can be provided; for example, infrared sensors measure thermal emissions and thus measure the temperature of an object. Since all materials emit heat radiation at various intensities, temperatures can be very important parameters for certain studies; for example, monitoring volcanic activity, water pollution, and ocean currents.

Finally, longer wavelengths such as microwaves are not blocked by clouds, as is visible light; and, like infrared, microwave sensors can be used at night as well as during the day, providing continuous information around the clock. By contrast, visual images are entirely dependent upon reflected sunlight, or a substitute for sunlight, and require clear atmospheric conditions.

It is recognized, of course, that much remains to be learned regarding the spectral signatures of various features on the Earth's surface. Energy absorption, emissivity, and reflectivity vary widely with climate and weather, as well as with the seasons of the year. A given object, therefore, may have a spectral signature that varies with time.

Additional complexities are introduced by the fact that the Earth's atmosphere (itself a variable absorber, reflector, and scatterer of energy at different wavelengths) imposes severe limitations on the capability of certain spaceborne sensors to observe features on the ground. Only those instruments will be useful that sense in the particular spectral regions where the atmospheric medium permits transmission of energy from the Earth's surface to the satellite at least some of the time.

SENSOR SYSTEMS

Remote sensors are the devices employed in spacecraft to detect and record the signatures of objects on or under the Earth's surface. Their proper combination and operation can provide the spectral, spatial, and temporal resolution needed to meet Earth resources survey data requirements.

The sensors under investigation and being used in the Earth Resources Survey Program include:

- photographic film cameras
- television systems
- multispectral scanners
- thermal mapping scanners
- imaging radar systems
- microwave radiometers

The sensors selected for any Earth resources mission should be chosen on the basis of the precision and sensitivity of the measurements required by the user and the ability to fly these instruments properly integrated with the spacecraft and its related subsystems. The problem regarding makeup of future operational sensor payloads is therefore one of judiciously selecting those instruments which will meet mission requirements in terms of user needs and cost considerations. The goal should be to collect the correct type of data but only in the amount necessary to solve the problem. To collect more data than necessary would overtax any analytical capability; eventually we must depend upon automatic processing of data.

THE NASA EARTH RESOURCES SURVEY PROGRAM (ERSP)

The ERSP is a broad program which includes laboratory and field experimentation and advanced studies, combined with aircraft and spacecraft observations, to establish the requirements for future experimental and operational systems. Specific program objectives include:

1. Establishing the information requirements that can be met with the new aerospace and instrumentation technology.
2. Developing a better understanding of the reflectance and radiation properties of biological and physical materials in the laboratory and in the field, and identifying the single or combined wavelengths that yield consistent measurements as they are acquired from progressively higher altitudes and from space.
3. Establishing a sensor-signature data bank based on an understanding of the modifying effects of the atmosphere as a function of Sun angle and look angle, as well as atmospheric constituents.
4. Developing sensor systems and data-processing methods that meet the needs of the resource scientist and manager.
5. Determining the complementary roles of spacecraft, aircraft, and ground platforms, and developing the technology required for future operational systems.
6. Developing, in concert with the user agencies, the ecological models necessary for understanding natural and man-caused events and forecasting their consequences.

It is obvious that in order to accomplish these objectives we need not only the physical scientist and engineer who can build space and aircraft instruments and platforms, but also the active participation of the user agencies (DoA, DoC, DoI, and Navy) as well as academic institutions and industrial organizations.

The R&D program is intended to maintain the flexibility to test promising competitive approaches and avoid irrevocable commitments that might cause expensive errors in these systems. The goal is to provide decision makers with the information they need for making long-term commitments.

The ERSP focuses on developing the understanding and expertise required for the use of remote sensing in the agencies and institutions charged with natural resources and environmental responsibilities and, through them, ultimate service to the public at large.

The various elements and their time-phasing in the ERSP are shown in figure 3. The early contributions of the ATS and Nimbus satellites, as well as the Gemini and Apollo manned programs, are included. The important Apollo 9 S065 experiment

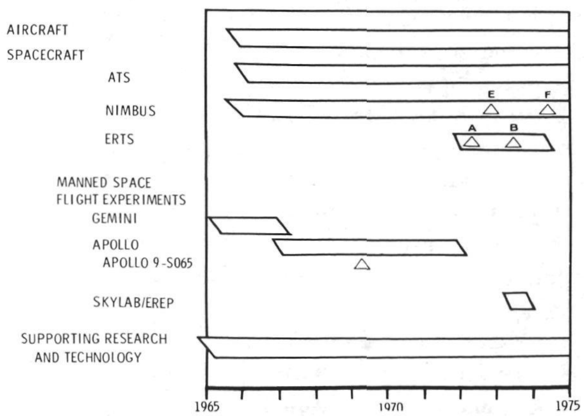


FIGURE 3. Schedule for Earth Resources Survey Program.

was the first dedicated multispectral photographic experiment from space; it is discussed later in this paper. The sustaining efforts in the aircraft program and in the supporting research and technology program are also included, along with the forthcoming ERTS-A and B and Earth Resources Experiment Package (EREP) missions.

From the beginning of the program, the ultimate users recognized the need to determine, by the processes of interdisciplinary research, whether in fact sensor technology would eventually meet operational requirements. It was also recognized that it was essential to develop the capability of utilizing the technology, which of course is the ultimate goal of applied research.

THE ROLES OF SPACECRAFT, AIRCRAFT, AND GROUND OBSERVATIONS

Four principal innovative features characterize the ERSP to date:

1. A spacecraft platform from which to obtain synoptic, repetitive viewing of the Earth's surface.
2. More precise quantitative techniques for multispectral measurement (from either spacecraft or aircraft) of electromagnetic radiation reflected and emitted from Earth surface features.
3. Techniques for automatically extracting information from remote sensing data.
4. Decision-oriented resource and environmental models that can make effective use of remote sensing data.

It is clear that any future operational system will depend on a combination of spacecraft, aircraft, and ground systems, which must be complementary rather than competitive, for both technical and economic reasons. For example, no one would deny the advantages of aircraft in gathering some types of high-resolution data over limited geographical areas or for statistically sampling those data requiring high resolution. High-resolution data gathering over extended regions may saturate any data-handling system, and should be avoided if at all possible.

From a purely technological standpoint, there are important reasons for utilizing the space platform. One concerns the effect of illumination angle on data gathering in the visible part of the spectrum, as shown by the mosaic of aerial photographs in figure 4. The individual pictures making up this mosaic were taken with the same camera and the same aircraft, at the same altitude, and processed with the same developing materials. The only change was time, and consequently solar illumination angle; the flight lines were made about three hours apart. While the terrain is known from ground truth to be essentially identical within each of the areas defined by the dashed lines, changing

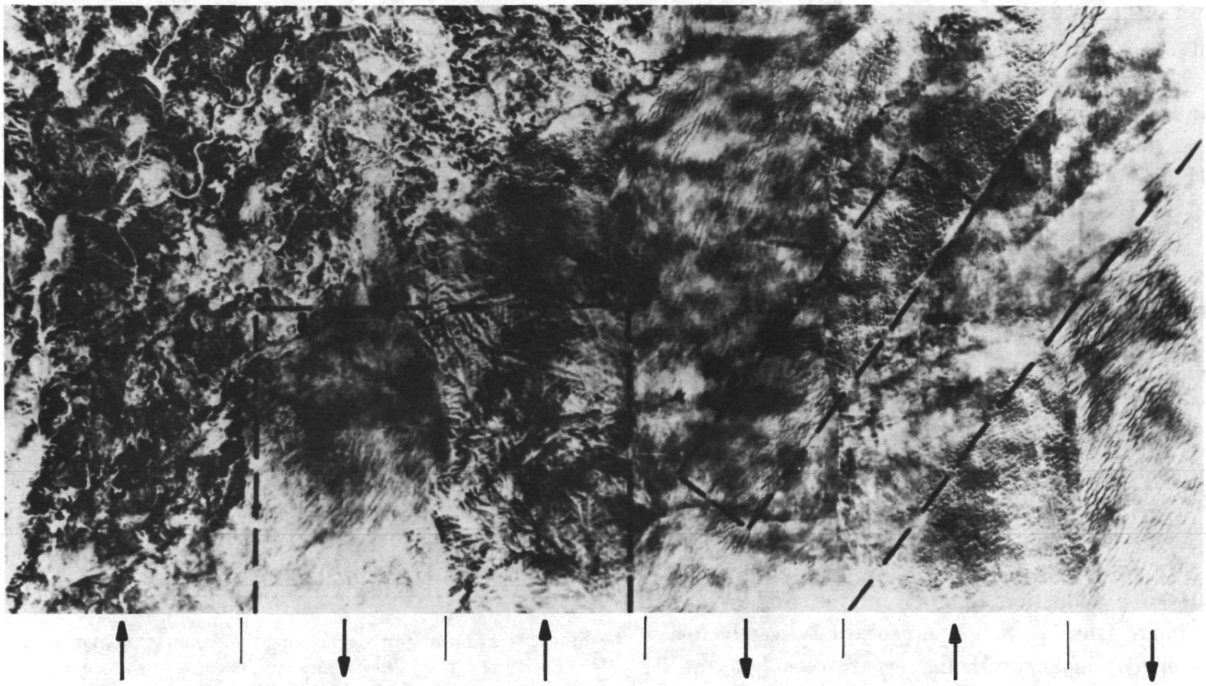


FIGURE 4. Apparent terrain differences in photomosaics may not represent actual differences. (Arrows show direction of flight.)

Sun angle makes the terrain look quite different. With Sun-synchronous satellite coverage, this problem would disappear. Like areas would look alike, both in spectral content and texture. This is obviously a significant advantage for terrain classification and thematic mapping—basic elements in all Earth science and important in applications to resource management.

Since analysis of the data for, say, thematic mapping represents a larger task, both technologically and economically, than gathering the data, the question of the presence or absence of geometric distortion in the basic data is very important. For many purposes imagery obtained vertically from altitudes of 13 kilometers or more above the Earth can be considered orthographic—that is, without rectilinear distortion. This fact tends to favor the use of spacecraft rather than aircraft for some applications.

For example, figure 5 shows a straight power line as it appears near the edge of a conventional aerial photograph and as it actually appears from directly overhead (lower image). There are two ways to map that power line properly. One is to apply to the upper off-axis view a complicated photogrammetric process to rectify the image, costing about $60 per image, and the other is to get farther away from the subject and obtain the narrow-angle view from space (above 130 km), where proper spatial relationships are better registered within the image. For this reason, properly acquired space data can give an "instant map," while aircraft data usually retain distortions that must be laboriously removed.

OFF-AXIS PERSPECTIVE-ANGLE VIEW

NEAR-VERTICAL PERSPECTIVE-ANGLE VIEW

FIGURE 5. The effects of perspective angle on relief displacement.

Taking into account the desirability of maintaining constant solar illumination angle and orthography, and of not overloading data systems with unnecessary inputs, it is believed that the economic and technical advantages of a spacecraft's contribution to surveys of areas approaching the size of the U.S. are significant.

The complementary role of aircraft and spacecraft in a broad class of inventory problems has been demonstrated. As an example, notable work has been done by the U.S. Forest Service in the application of Apollo 9 spacecraft photographs, together with concurrent aircraft and ground data, to a practical, operational problem of timber inventory. A brief summary of the conclusions will demonstrate the strength of such coordinated spacecraft, aircraft, and ground survey efforts.

The inventory of 20 000 square kilometers demonstrated a reduction in error in the timber-volume estimate from 31 to 13 percent, due directly to use of space imagery. If the error were held at 31 percent, the savings could be reflected directly in aircraft-hours and manhours required to complete the inventory with a fixed expected error. It has been estimated that use of the Apollo 9 photography could reduce the required aircraft and ground data gathering effort by a factor of six.

This statistical multistage (coordinated spacecraft, aircraft, and ground observations) technique is applicable to a broad class of Earth resources inventory problems.

This multistage approach is also necessary in our research program, as illustrated in figure 6. We include theoretical analysis, laboratory experimentation, field measurements of selected ground targets, measurements from aircraft at increasing altitudes, and finally, measurements from spacecraft at orbital altitudes. All of these concurrent approaches are essential to ensure a sound R&D program as well as to indicate the appropriate roles of spacecraft, aircraft, and ground-based observations in future operational systems.

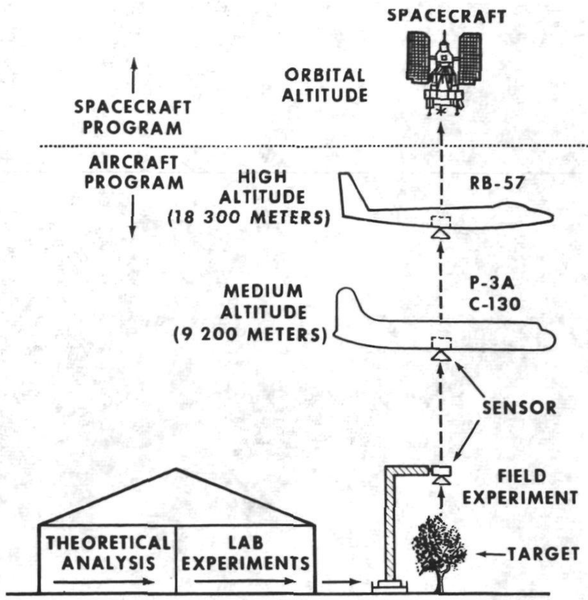


FIGURE 6. Continuing development of remote sensor techniques.

THE AIRCRAFT PROGRAM

The NASA Earth Resources Aircraft Program (ERAP) is illustrated in figure 7. To date, this program has produced most of the experimental data used by resource scientists in defining and developing remote-sensor systems for aircraft and spacecraft, and in determining the specific roles of spacecraft, aircraft, and ground systems in future operations.

The aircraft is a highly adaptable test platform for determining the performance and usefulness of sensors under development. Instead of waiting for data acquired from spacecraft, users are presently obtaining multispectral data of Earth phenomena from sensors carried by NASA aircraft. These data are used to evaluate the sensors and to develop a solid foundation for observational and interpretive techniques for Earth resources space missions.

The ERAP currently includes three aircraft: the RB-57F, the NP-3A, and the NC-130B. We shall shortly add two more high-altitude (U-2) aircraft to the program. These high-altitude jet aircraft, such as the RB-57F shown in figure 8, permit us to simulate closely the conditions expected from an orbiting spacecraft, since they are capable of flying above 90 percent of the Earth's atmosphere and obtaining a fairly large field of view from altitudes of about 18 kilometers. The lower-flying aircraft are used primarily for instrument development and early research in sensor-signature relationships.

The Lockheed C-130B is our flying optical and infrared laboratory. This aircraft will carry a 24-channel multispectral scanner, which should provide

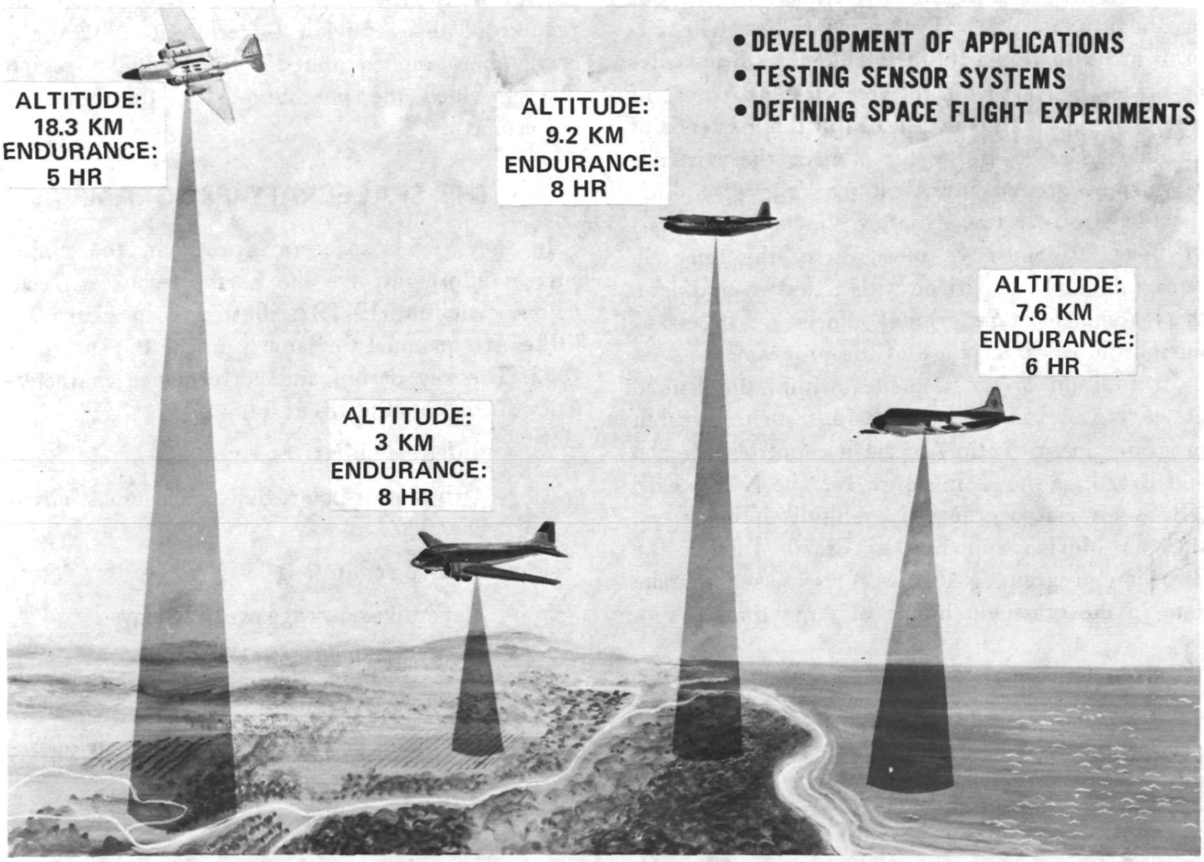


FIGURE 7. Goals and capabilities of the Earth Resources Aircraft Program.

a wide range of information about the nature of the signatures used to separate, classify, and identify specific Earth resources. This instrument is an expansion of the 12-channel scanner used in the University of Michigan C-47 aircraft, which we also use for the same purposes. The NP-3A is our radiowave instrument development laboratory. It has a large number of radio antennas mounted on

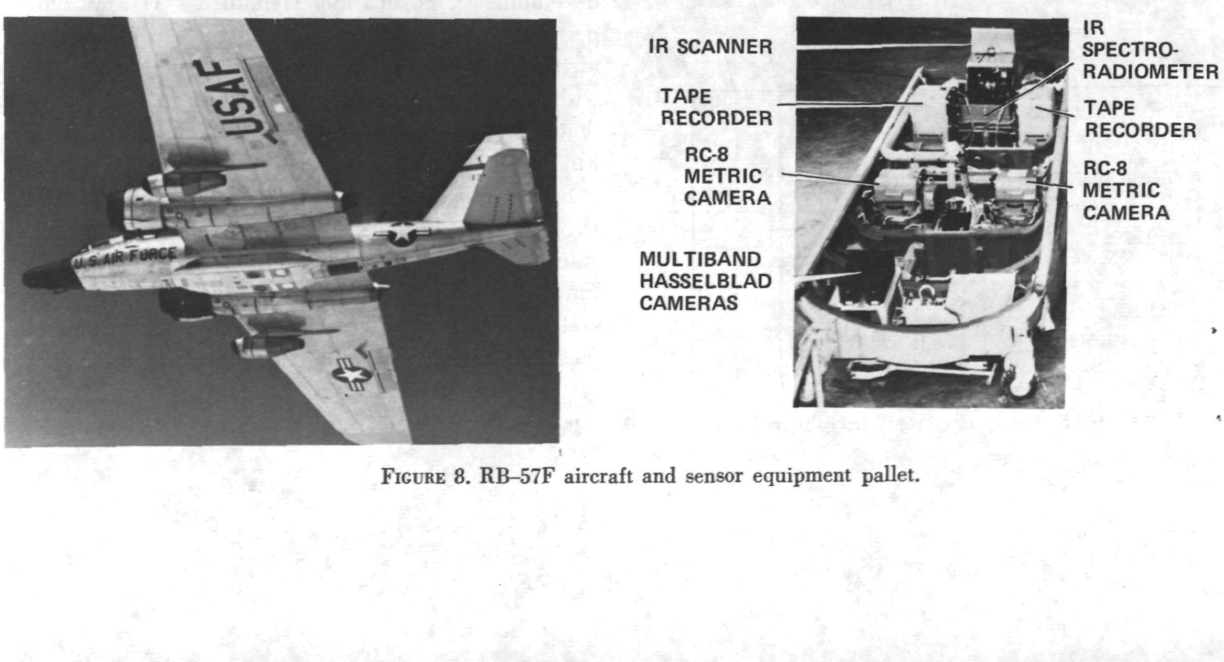
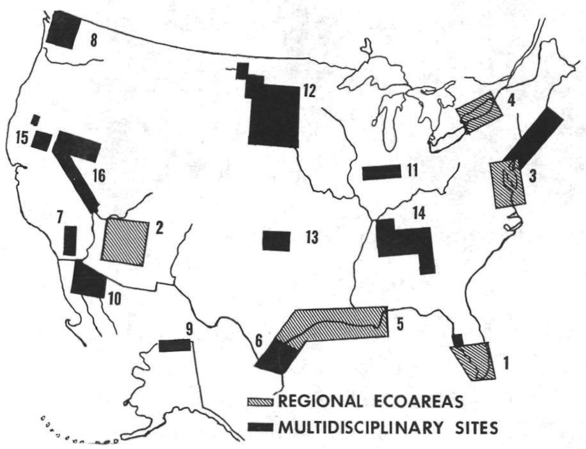


FIGURE 8. RB–57F aircraft and sensor equipment pallet.

its underside, and it is used extensively in our oceanographic and hydrological studies. The aircraft are used primarily over a number of test sites or areas (figure 9) which were chosen because of interest in the area and because of the existence of available data regarding the area or the existence of current ground investigations. The disciplines included in these test areas are shown in the chart of figure 9. Since we must verify the remotely sensed data by comparison with actual ground data, these complementary ground efforts are necessary during the research phase of the program.

In addition to the test sites within the United States, NASA has cooperated with test-site research programs in two Latin American countries, Mexico and Brazil, as shown in figure 10. The NASA ERS NP-3A aircraft overflew six multidisciplinary test sites in Mexico and five in Brazil. During the Brazilian program, NASA was also asked to take data in the grassland biome of Argentina in support of the International Biological Program. At the request of the Peruvian Government, NASA aircraft photographed the 1970 earthquake region and provided the photographs to the Peruvian Government.



SITE / IDENTIFIED INTEREST	REGIONAL ECOLOGY	ENVIRONMENTAL QUALITY	GEOGRAPHY	GEOLOGY	HYDROLOGY	AGRICULTURE	FORESTRY	OCEANOGRAPHY	MARINE BIOLOGY
1. SOUTH FLORIDA	X	X		X	X	X	X	X	X
2. PHOENIX	X	X	X	X	X	X	X		
3. CHESAPEAKE BAY	X	X	X		X	X	X	X	X
4. LAKE ONTARIO	X	X			X			X	
5. GALVESTON/BILOXI	X	X	X		X			X	X
6. WESLACO						X			
7. IMPERIAL VALLEY						X			
8. PUGET SOUND		X	X	X	X		X	X	X
9. NORTH SLOPE				X	X			X	
10. GULF OF CALIFORNIA								X	
11. CORN BELT					X	X			
12. WHEAT BELT						X			
13. CHICKASHA						X			
14. EASTERN FOREST- TVA					X		X		
15. WESTERN FOREST							X		
16. ARID LANDS			X	X	X	X			

FIGURE 9. Regional and multidisciplinary areas.

THE SPACECRAFT PROGRAM

In the NASA spacecraft program, the major current efforts involve the Earth Resources Technology Satellite (ERTS), illustrated in figure 11. ERTS-A is planned for launch during the spring of 1972. The key design and performance characteristics of this satellite are as follows:

- Lifetime objective: 1 year
- Orbit: near-polar, Sun-synchronous, circular, 920 km
- Attitude control $<0.7°$
- Repetitive coverage every 18 days
- Sensor payload: 240 kg
- Total weight: 865 kg
- Minimum power (20-minute sensor operation per orbit)
- Wideband data transmission: 20 MHz, S-band
- Onboard data recording
- Orbit adjust capability

The Sun-synchronous near-polar orbit will permit the satellite, with its narrow-angle sensors, to observe the same spot on Earth once every 18 days. It also means that observations will be made with a nearly constant solar illumination angle, required for developing identification signatures. The altitude permits narrow-angle sensors to be used to obtain virtually undistorted images. Data from the satellite will be received by ground stations in the United States and processed at the NASA Goddard Space Flight Center (GSFC) in Maryland.

Since reliance must be placed on readout from U.S. ground stations, the gathering of data outside the U.S. will depend largely on the reliable functioning of an onboard video tape recorder system. Thus, tape recorder capacity is the principal factor in determining the extent to which the ERTS system can provide data from areas beyond the line-of-sight range of our U.S.-based receivers.

FIGURE 10. Foreign cooperative test site research.

FIGURE 11. The Earth Resources Technology Satellite (ERTS).

The spectral bands, spatial resolution, and orbital parameters of ERTS are based on experience with our aircraft research programs and a single multispectral film experiment carried into space on the Apollo 9 flight. The 185-by-185-kilometer imagery format from spacecraft altitudes provides sufficient orthography for many applications, and the near-polar orbit provides a minimum of 10 percent overlap of successive passes at the equator.

The sensors or instruments to be carried on ERTS-A include a high-resolution return-beam vidicon (RBV) television system to record images in three regions of the visible and near-infrared spectrum for the preparation of thematic maps over large surface areas. The ground resolution of the television system is expected to fall in the range of 92 to 185 meters.

A four-channel scanner extends spectral coverage to important longer infrared wavelengths and permits analysis at the level of each resolution element. Besides providing radiometric data not available from the television camera system, the scanner data is inherently compatible with automated analysis by digital computers. The data is recorded digitally

aboard the spacecraft, and the single collecting optics provide essentially perfect registration between spectral channels.

The feasibility of automatically classifying various Earth-resource phenomena has been demonstrated by experimentation with aircraft scanner data. The ERTS-A scanner will provide a means to test techniques of automated information extraction from data acquired at orbital altitudes on a repetitive basis. The ERTS-B scanner will also have a thermal-infrared channel. The data taken outside the line-of-sight range of the three United States data-acquisition stations by the RBV system and the multispectral scanner can be stored on a wideband video tape recorder for later transmission.

Experience with Nimbus and studies for the Synchronous Meteorological Satellite (SMS) have indicated the feasibility of satellite data collection from ground sensors, and such a data collection system was selected for ERTS-A. This system will collect and relay data from Earth-based sensors for analysis with the spacecraft remote-sensing data. Typical ground sensors will measure and transmit to ERTS-A such parameters as stream flowrates, water content of snow, soil moisture, and temperature. ERTS-A will receive this data and transmit it to ground receiving stations, where the data will be analyzed and correlated with the RBV and scanner images.

Experimentation in the laboratory, in the field, and by aircraft over the years, as well as analysis of photography by Apollo 9, strongly support the prospect of success for the ERTS-A and B. These spacecraft should return data that can be used to produce photoimages useful in the analysis of such subjects as regional geological structures, land use, land-water interfaces, and changes in vegetation. The repeated coverage by ERTS-A and B orbits at higher latitudes will also allow useful information to be extracted about variations in snow cover, as related to water runoff rate and abundance. The data from ERTS-A and B will be evaluated to determine the usefulness of space-derived remote sensing data to these areas of interest.

While ERTS-A is operating, aircraft will provide additional details to supplement and support spacecraft-acquired data. The aircraft data will be in the form of samples from selected areas and information on the spectral signatures that require more frequent coverage of locales or greater resolution than can be obtained from the satellite.

Data acquired from ERTS-A and B will be made available to all selected investigators directly and to others on a cost-of-duplication basis. An "Announcement of Flight Opportunity," issued in June 1970, provided potential investigators with the opportunity to propose studies based on ERTS-A and B data. It has received wide circulation here and abroad. To date, over 400 letters of intent have been received, including about 70 letters from 30 foreign nations and international organizations. A conference for potential investigators held at GSFC in February 1971 attracted over 650 registered attendees, including over 30 from 20 foreign countries and international organizations.

As mentioned earlier, the ERSP has also employed manned spacecraft for acquiring data. The early hand-held camera and automatic color photography from Mercury, Gemini, and Apollo provided imagery which a number of scientists in universities, industry, and government found of great interest. In particular, geologists found that these large-area, small-scale images revealed features never before identified. This work led to the design of the first controlled multispectral photography experiment, which was carried out during March 1969 on Apollo 9 to verify the choice of spectral bands for the ERTS sensors.

The next observational experiments on a manned mission will be aboard Skylab, the first manned orbital workshop, to be launched in 1973. Exploratory studies of selected ground targets will be made with a group of sensors which comprise the Earth Resources Experiment Package (EREP), illustrated in figure 12. Since Skylab will fly during the life of ERTS, data from these Skylab sensors will be compared with data from airborne flights and ERTS. The Skylab will permit us to place in orbit more sophisticated sensors covering many more regions of the spectrum than ERTS.

EREP sensors include an array of six boresighted cameras, an infrared spectrometer, a 13-band multispectral scanner, a 13.9-GHz radiometer/scatterometer, a 13.9-GHz radar altimeter, and a 1.4-GHz radiometer. Several of the photographic bands and several of the bands of the multispectral scanner correspond to the bands selected for the ERTS television system and scanner, thus permitting correla-

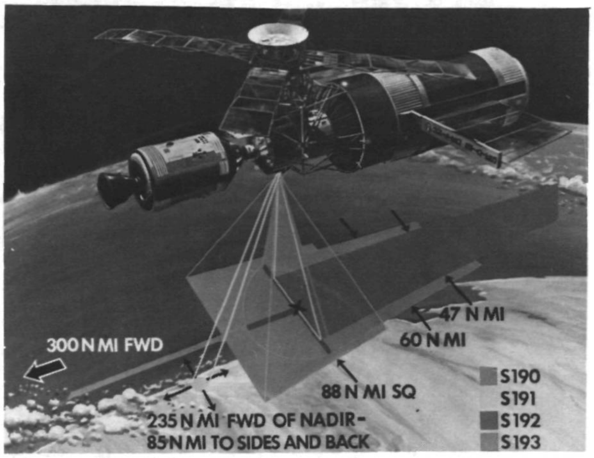


FIGURE 12. EREP ground coverage.

tion of EREP photographic and scanner data as well as EREP and ERTS data.

Skylab will be placed into circular orbit at a 50-degree inclination and an altitude of 436 kilometers. The first three-man crew will rendezvous with Skylab a few days after the unmanned launch and will spend 28 days in orbit. Subsequent missions to Skylab are planned for 90-day centers, with the second and third crews each spending 56 days in orbit. During the uninhabited periods, EREP will be deactivated. EREP film and tape records will be returned to Earth with the crew in the command module, and film and tape will be replenished on return flights. On the final mission, the crew will return the filters used with the multispectral camera, for ground calibration. Because of the orbit, EREP data will be acquired only between the 50-degree latitudes and under varying solar illumination conditions. Because the data must be physically returned to Earth via the reentry capsule, the amount of data to be acquired is limited.

An "Announcement of Flight Opportunity," issued in December 1970, gives investigators an opportunity to call for special observations or studies using EREP data. Plans have been made for an integrated review and evaluation of the ERTS and EREP data-utilization proposals to make the most of these two complementary missions. EREP data will be made available in the same manner as ERTS data.

The large and rapidly increasing amount of data on Earth resources collected in the ERSP constitutes an extremely valuable, unique source of information. To provide access to this mass of data for study by investigators and other interested parties, an ERS research data facility was established in January 1969 at the NASA Manned Spacecraft Center. The facility has already been utilized by many industrial and commercial organizations, educational institutions, United States Government agencies, and foreign governmental and private organizations.

INFORMATION PROCESSING

A key portion of the program is concerned with information processing. The goal of the program is not data, but rather information from which sound resource and environmental management decisions can be made. Thus, the extraction of information from data at the earliest point in the system in the most efficient manner is a primary goal. This work depends on both sensor-signature research and on the development and use of decision-oriented resource and environmental models that can exploit remote sensing data.

Experience gained from over 30 years of intensive use of aerial photographs has shown that panchromatic (minus blue) photography helps determine *where* things are, but (at least in terms of natural phenomena) has only limited success in determining *what* things are. On the other hand, in little more than five years, multispectral imagery has made significant progress in classifying and, in some cases, identifying natural surface phenomena. It should be noted that sequential coverage also aids in this identification.

Although powerful, these newer techniques create two important problems. The first is that machines must be used to perform quantitative radiometric measurements and also to assist in the interpretation of such measurements, since man has difficulty in evaluating spectral changes. The second is that multispectral data analysis requires high rates of data transmission and manipulation.

Because of these two problem areas, a major effort in the experimental program concerns data compaction, compression, and sampling (some of which may be done aboard future spacecraft). Studies are also underway on data processing, reformatting, filing, storing, accessing, and retrieving, as well as studies to detect surface changes by

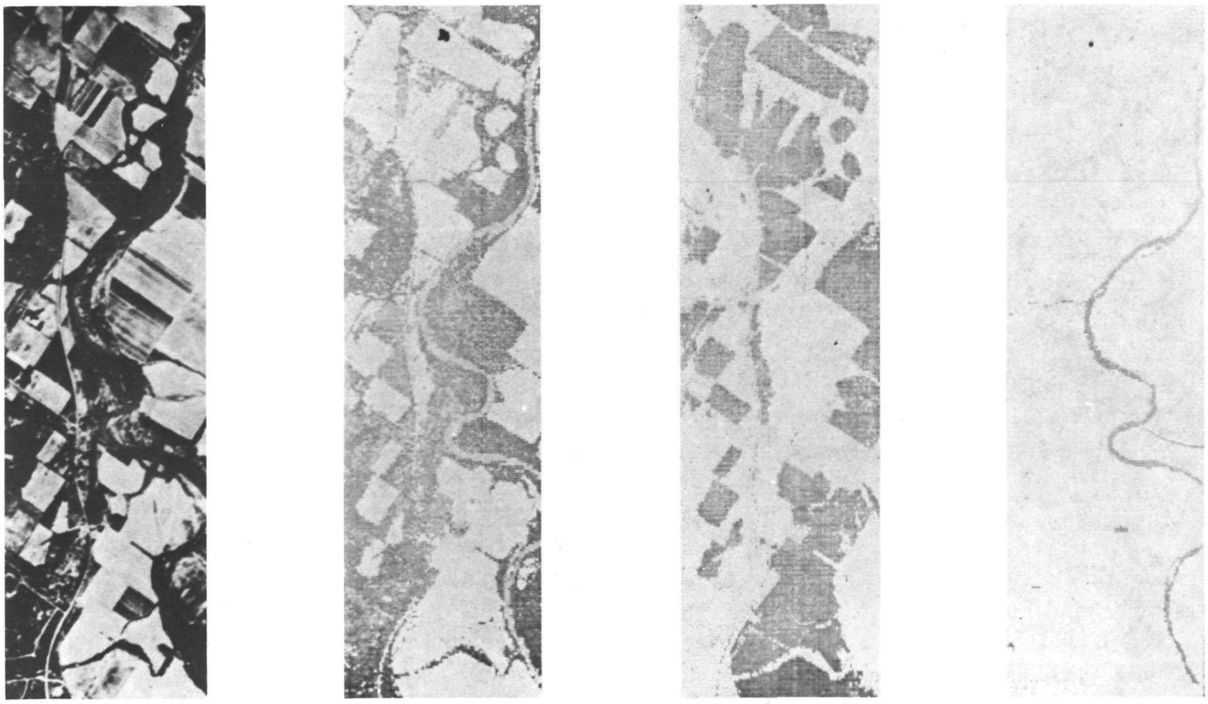


FIGURE 13. Automatic classification of green vegetation, trees, soil, and water.

analysis of the sequential data. Data-compression techniques will make it possible to store information on changes in data without duplication.

Significant progress has been made in automatic classification of Earth features using digitized data from a multispectral scanner. Much of this work is being carried out under NASA sponsorship by the Laboratory for Applications of Remote Sensing (LARS) at Purdue University, using the multispectral scanner and aircraft of the University of Michigan. Green vegetation, trees, soil, and water can be classified automatically with this system (figure 13), as well as certain crop types such as corn, soybeans, wheat, and oats (figure 14).

During the summer of 1970, aircraft scanned areas of Indiana infested with southern corn leaf blight (spore-carried fungus) which destroyed about 15 percent of the U.S. corn crop in that year. (The problem is likely to continue into 1971, since a sufficient amount of blight-resistant seed will not yet be available.)

As shown in figure 15, processing of aircraft data identified five significant levels of crop stress, and when the aircraft data were combined with ground

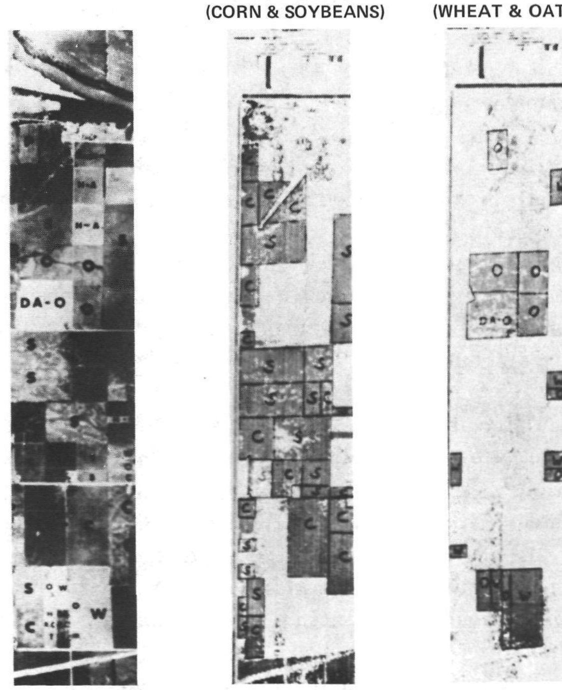
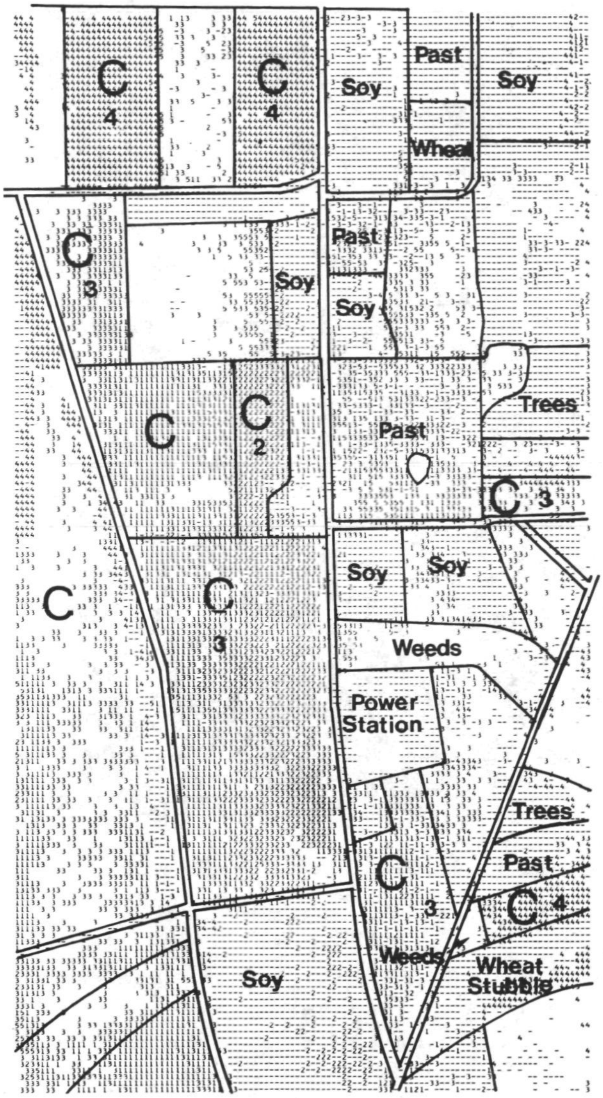


FIGURE 14. Spectral pattern recognition of row crops and cereal grains.



KEY TO STAGE OF INFECTION:

1=VERY MILD
2=MILD
3=MODERATELY SEVERE
4=SEVERE
5=VERY SEVERE
DASH=IDENTIFIED BUT NOT CORN
BLANK=UNKNOWN

FIGURE 15. Automatic identification of corn leaf blight.

observations, it was established that the stress identifications represented five levels of southern corn leaf blight infestation. Remote sensing shows great promise for detecting such crop diseases early and minimizing losses by early harvesting, spraying, and identification of sources of blight-resistant seed.

Computer printouts have illustrated some promising results in automatic soil classification (figure 16). Digitized images processed from line-scan imagery showed that classification of soils by standard color indexes showed better than 90 percent correct correlation with the classification according to organic-matter content derived from ground measurements.

The Purdue/LARS automatic digital classification techniques are being extended into the geological area by investigators of the USGS. Ten terrain classes have been identified in a test area within Yellowstone National Park, as shown in figure 17. The classification at the top of the chart used an optimum set of four spectral bands; the bottom one used the three proposed ERTS bands. The ERTS bands produced very nearly the same accuracy (82 percent) as the four optimum bands (86 percent). These results give considerable promise for automatic terrain classification from ERTS data.

These capabilities for automated classification from aircraft may be extended to spacecraft observations. The extent to which this can be accomplished will be determined in the analyses of ERTS-A and B data.

Some rather convincing evidence of the applicability of automated classification techniques to spacecraft observations has already been obtained from the Apollo 9 experiment in March 1969. A typical multispectral product is shown in figure 18. These and similar data have been used to verify the capability of the green band for water penetration, the red and near infrared bands for crop and feature identification, and the near infrared band for plant-stress detection and identification of surface water.

It has also been possible to digitize the Apollo 9 data and, applying the LARS techniques, automatically classify various terrain categories such as vegetation, basalt, alluvium, and sand dunes. Figure 19 shows (as used on the cover of *Astronautics and Aeronautics* magazine for April 1971) a full-color reproduction of this computer printout for the Imperial Valley area of California. Taking a portion of this area and further applying the LARS computer classification technique, it has been possible to

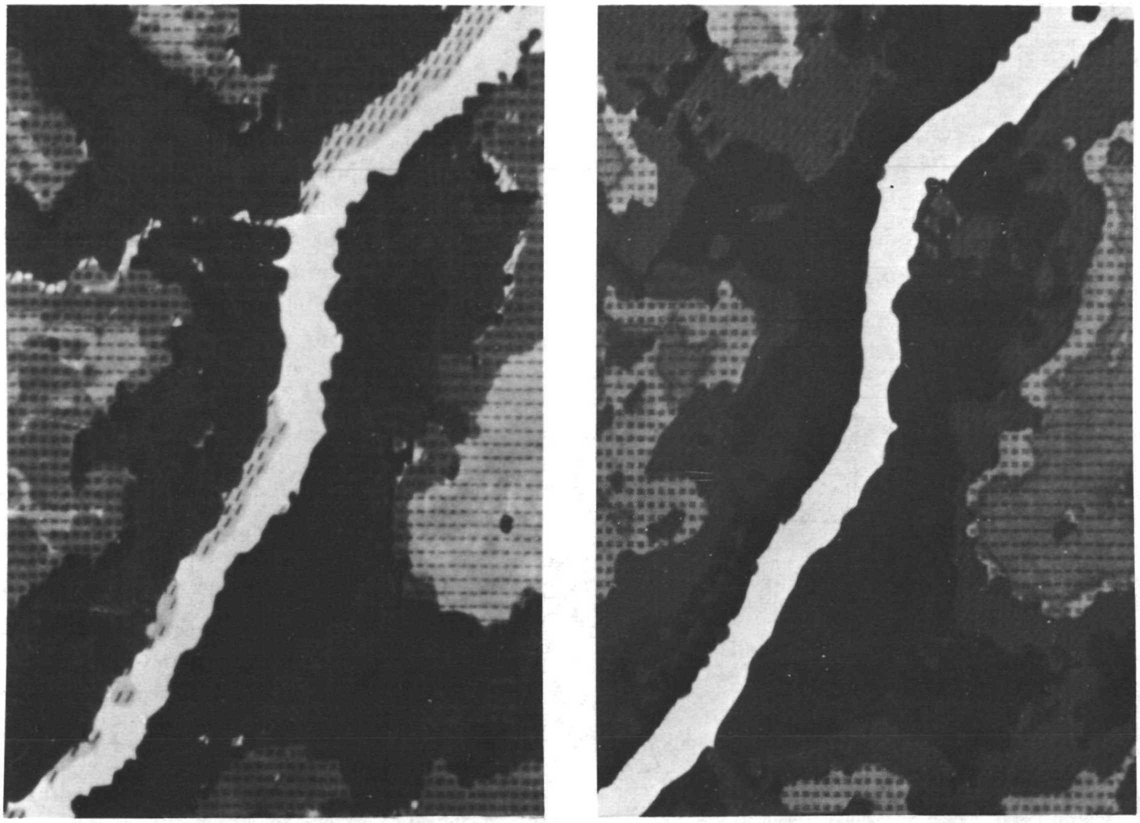


FIGURE 16. Automatic soil mapping. Left photo shows computer printout of seven soil categories based on spectral properties. Note correlation between soil color map and soil organic matter map (right) derived from ground measurements.

identify green vegetation, soil, and water (figure 20).

In addition to verifying the choice of spectral bands for the ERTS television cameras and performing automated terrain classification, the Apollo 9 experiment served to evaluate the feasibility of simultaneous spacecraft-aircraft imagery and sequential aircraft imagery for inventory and classification of resources. The areas of the United States over which simultaneous spacecraft and aircraft imagery was obtained include the Imperial Valley and Mesa, Arizona, agricultural test sites, and the area in Mississippi, Louisiana, and Arkansas covered by the Forest Service (USDA) in the timber-inventory study. Analysis of color infrared imagery taken from spacecraft, high-altitude aircraft, and low-altitude aircraft gave a most significant result: The tonal signatures evident in the aircraft imagery are well preserved in the small-scale spacecraft imagery, and tonal signatures when combined with sequential coverage have established the feasibility of constructing crop calendars. A typical calendar is shown in figure 21. This information can be used to facilitate species identification, as well as vigor and yield estimation.

Based on the experience gained from the Apollo 9 multispectral photography experiment, with resolution comparable to that of ERTS, we are confident that these techniques can be employed to extract similar vegetation and terrain classifications from ERTS and EREP data.

FUTURE SYSTEMS

The converging lines of ERSP activities—laboratory and field experimentation, advanced studies, aircraft and spacecraft observations—aim at determining the desirability of an operational ERS system, as well as its optimum configuration in terms

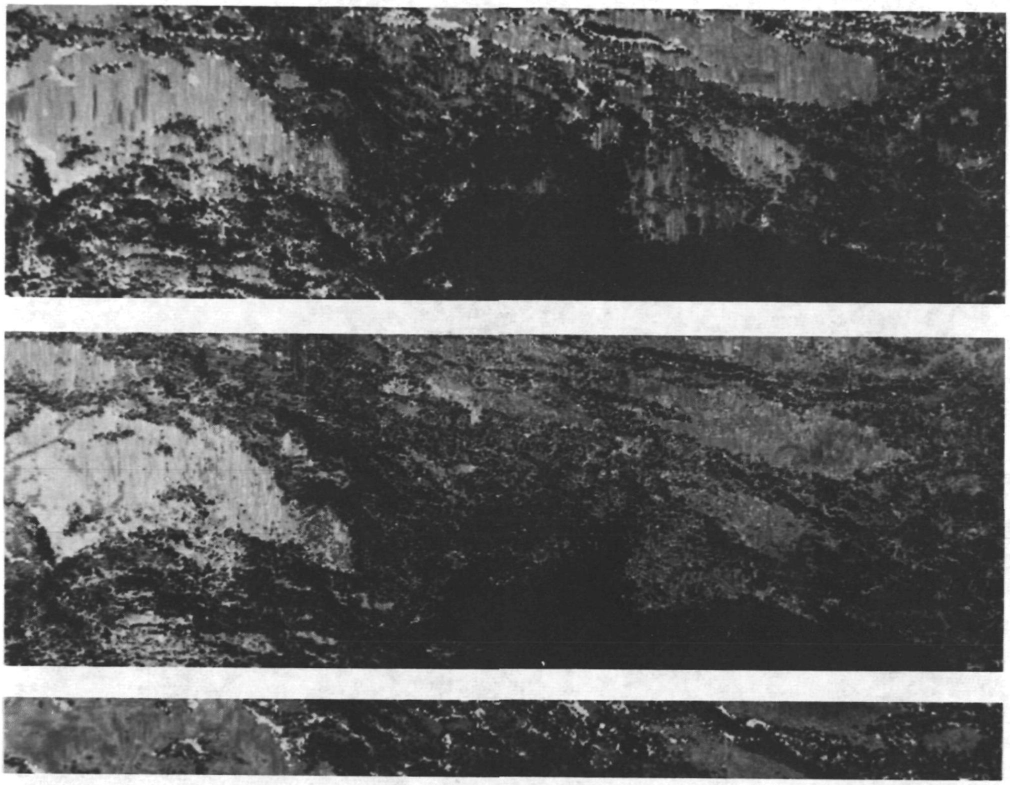


FIGURE 17. Automatic classification of terrain (Yellowstone National Park) by Michigan multichannel scanner and Purdue computer.

of aircraft, spacecraft, and ground segments. Continuing research and development with spacecraft and aircraft will be necessary to ensure that improved concepts and technology can be utilized to upgrade operational systems. Additional research spacecraft beyond ERTS-A and B are anticipated.

The advisability of establishing operational systems will depend primarily on the management value of the resource and environmental information from this program. NASA is working jointly with users in developing an adequate set of experiments to determine this operational value.

The aircraft program, ERTS, and EREP/Skylab provide a broad range of experiments with various combinations of space, air, and ground data-acquisition systems. This experience is essential to developing the best total ERS system concepts, and many promising techniques will probably depend upon experimental observatory-type spacecraft beyond ERTS-A and B for verification of utility.

To understand fully the requirements for research systems and the scope of future operational systems, it is necessary to construct conceptual models of the "total" system. Such a model is illustrated in figure 22. An important part of the program must deal with the development and validation of decision-oriented resource and environmental models that can make the most effective use of remote sensing data—the output of the observation system.

Model studies are presently being conducted in agriculture, forestry, range management, hydrology, geology, geography, and oceanography. In the larger context, these studies deal with measuring and monitoring the dynamics of terrain and ocean

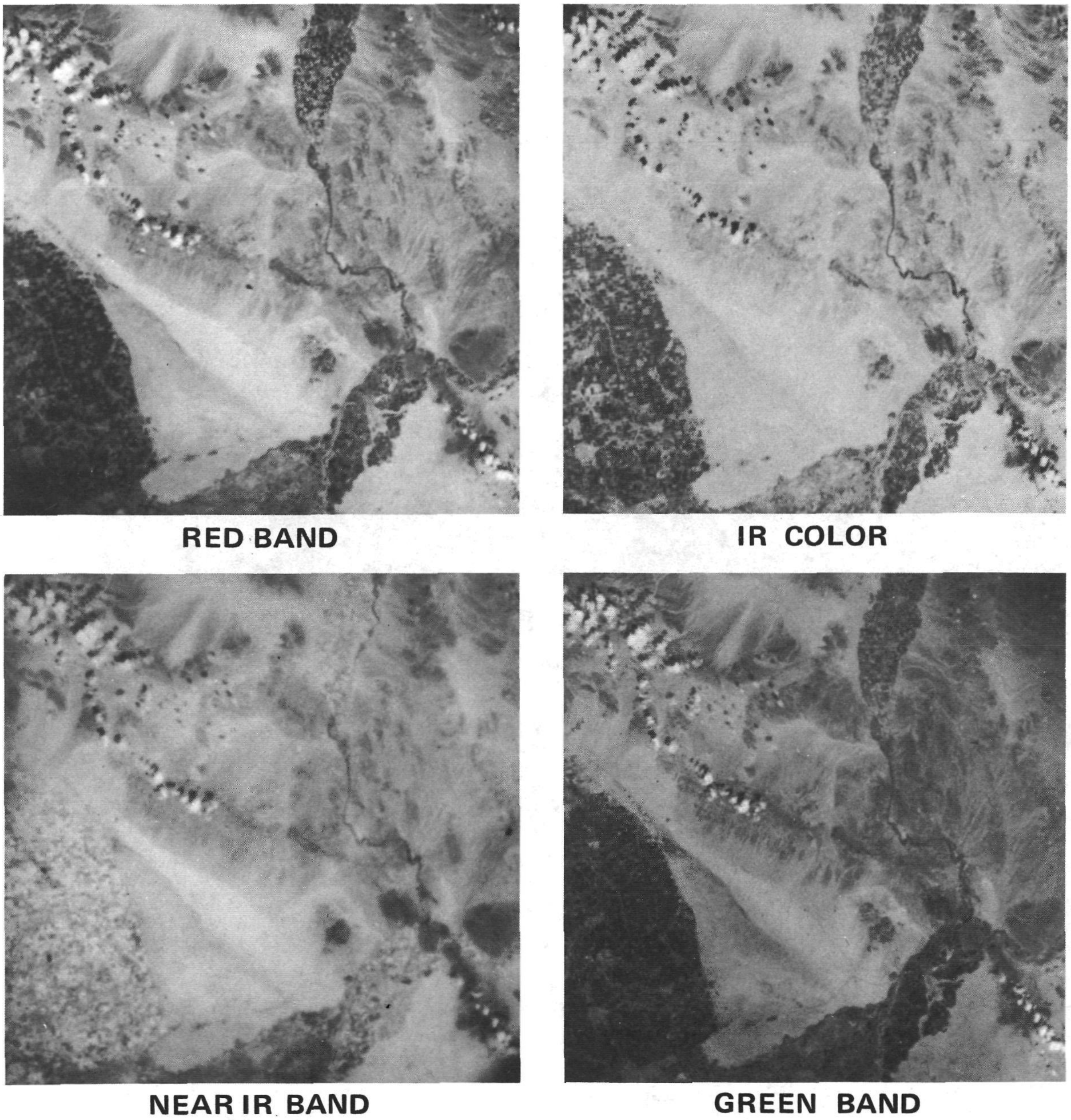


FIGURE 18. Apollo 9 photographs of Imperial Valley, California, taken in March 1969 using the S065 multispectral camera.

surfaces and, to a small degree, the subsurface, for there is a clear connection between geologic structure, soil formation, the hydrologic cycle, and vegetation.

Using available modeling techniques, contractual studies have analyzed several promising applications: regional water management, wheat-production management, and wheat-rust control. These need refining and verification, and many other studies need to be undertaken.

We feel, however, as did the National Academy of Sciences in its 1968 study on "Useful Applica-

FIGURE 19. Apollo 9 computer map of Imperial Valley region.

FIGURE 20. Automatic classification of Apollo 9 imagery.

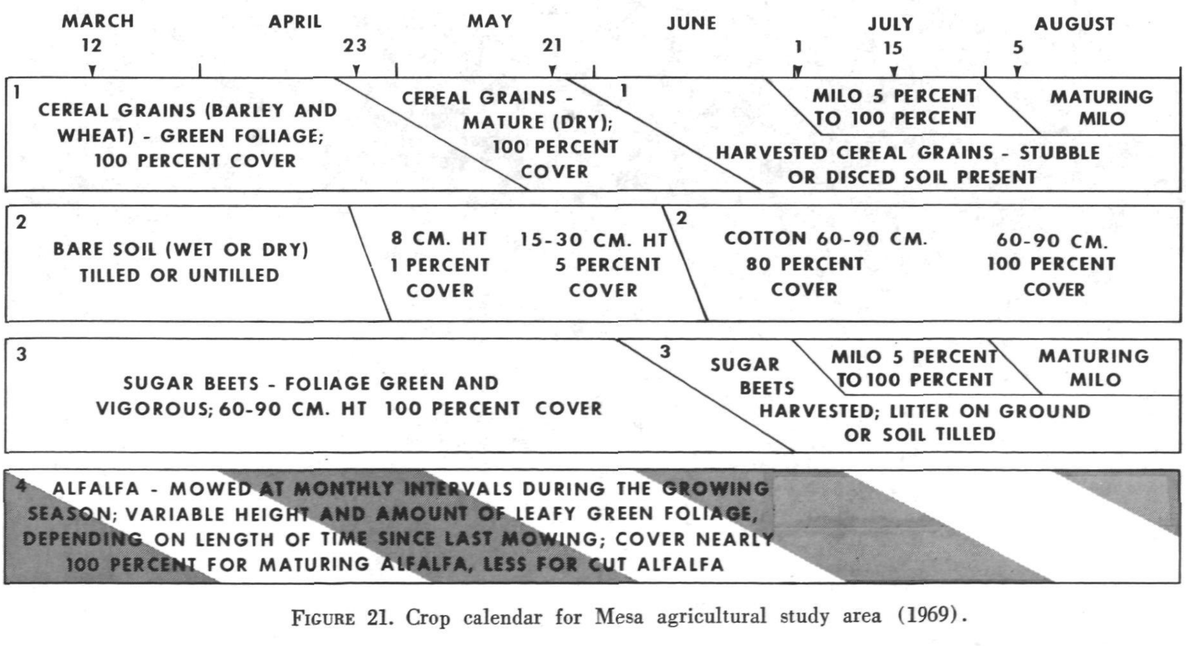


FIGURE 21. Crop calendar for Mesa agricultural study area (1969).

tions of Earth-Oriented Satellites." The Central Review Committee conclusions and recommendations state: "The benefits from space application are expected to be large—larger than most of the study participants had originally believed, and certainly larger than the costs of achieving them."

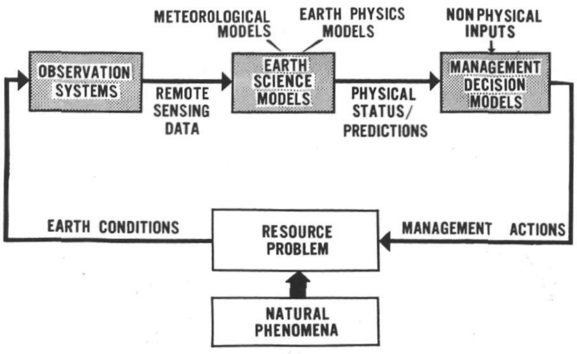


FIGURE 22. Block diagram of an operational ERS system.

In conclusion, it is most important not to lose sight of these essential facts: Since the current programs are research programs, data formats and characteristics may differ markedly from follow-on research programs or operational systems. The ERTS program is intended primarily to gather data over the United States and nearby ocean areas; the gathering of significant data outside the United States will depend on the specific proposals for such investigations and on the successful and continued functioning of an onboard video tape recorder system.

All results will be published in the open literature, and all data acquired will be made available, to insure that the benefits of this program will accrue to the world community, as is fitting in such a scientific endeavor.

International Aspects of the Earth Resources Survey Program

ARNOLD W. FRUTKIN

Assistant Administrator for International Affairs, NASA

Perhaps it is appropriate, as we begin this international examination of a very promising new discipline, that I offer largely cautionary remarks which you may keep in the backs of your minds during the next two weeks.

To begin with, this is the first International Workshop on Earth Resources Survey Systems. It is a direct descendant of the International Meteorological Satellite Workshop, held in Washington in November 1961 and sponsored by NASA and the U.S. Weather Bureau. Representatives of over 30 countries were represented then. The purpose was to help prepare the international community to use weather satellite data, just as this workshop is to prepare for the use of Earth resources satellite data.

The earlier workshop was held after three weather satellites had proved themselves. This workshop comes about a year before the first dedicated Earth resources satellite will be in orbit. In a sense, then, this workshop could be considered too early. On the other hand, the evidence of the preliminary space and air programs in remote sensing led us to believe that the workshop was needed so that you could decide for yourselves what expectations you should have in the Earth resources survey (ERS) field and how fast and extensively to prepare yourselves.

Second, I should note that both the earlier workshop and this one were designed exclusively as technical meetings. We are prepared here only for technical matters and will have to leave other matters to other forums.

Third, I should point out that the presentations during this workshop will be given principally by people who have been deeply involved in the development of the ERS program. They are therefore *advocates* and must be understood as such.

Fourth, I probably don't need to remind you that this new technology should not be considered in isolation. It is one of many tools available for resource and other economic development. We do not mean to suggest here what priority these new techniques should have in your own country. This is a judgment which we must leave to you.

Next, I want to commend your attention especially to the fact that we have scheduled one day, Thursday, May 6, for presentations by representatives of other countries. Their views and experience may well be of even greater relevance to you than our own by reason of scale in budgets, in geography, or in technical resources.

Let me turn now to the prospects for international use of Earth resources data through remote sensing. Such use will depend on (1) the availability of data, (2) the value of the data, and (3) the capabilities to use the data.

You already know there are three sources of data: (1) satellites which have already flown, such as Nimbus, TIROS, Gemini, Apollo, etc.; (2) aircraft; and (3) the Earth Resources Technology Satellite (ERTS).

The early experimental satellite data, which are cataloged and available, were good enough to encourage the U.S. Government to initiate a satellite remote sensing program. However encouraging these data have been, they are of course experimental. They were not intended to be and are not comprehensive, continuous, or systematic. So, while the

data are available, they did not and do not constitute an ongoing international service.

If we turn to the U.S. aircraft remote sensing program, we see that most of the data have been acquired over U.S. sites, with the purpose of developing recognition patterns and calibrating instrumentation. Some data have been acquired internationally, but on a very limited basis. Again, this activity is not in a real sense a source of supply for the general international community. Yet the data are available, either in copies or for consultation at our centers, and can serve research and educative purposes.

This brings us to ERTS, our first satellite project to be dedicated to resource and environmental sensing. You have just heard from Mr. Jaffe on the objectives of this project. Let me repeat them briefly. They are to confirm and assess the practical value of remote sensing from space; to compare the remote sensing capabilities of spacecraft and aircraft; to determine whether and how an operational Earth resources survey system should be pursued, using space elements for the purposes of a user community; to determine which remote sensors are most effective; to develop data handling procedures; and to help us understand operational system requirements and costs. These objectives point out that the ERTS system is an inquiry and not an indefinite commitment to collect and provide data.

This raises a number of obvious questions in an international audience. Let us look at some of them:

Question: When does ERTS data become available?

Answer: In 1972, if all goes as planned.

Question: What will be the value of these data?

Answer: We cannot be certain yet, since one of the purposes of ERTS is to determine exactly this. Of course, some informed estimates can be made, and you will be hearing these in some detail during the course of the workshop.

Question: What will be the international availability of the data?

Answer: In principle, all the Earth resources data gathered will be made available. For practical purposes, the amount and location of data actually collected will depend on the lifetime of the satellite, the lifetime of the tape recorders, the number and quality of research proposals for the collection of data for areas outside the United States, the spacecraft power budget, and the time required to read out the broadband telemetry. If spacecraft data acquisition time is limited for any of these reasons, the schedules will be adjusted to meet ERTS' primary objective: to gather data over U.S. ground truth sites which have been used for the aircraft program, so we can cross-calibrate the data and meet other requirements of the U.S. user agencies.

Question: Will other countries be able to read out the ERTS data if they wish?

Answer: Yes, if they choose to invest in the necessary ground receivers. In fact, Canada has decided to do this, and we expect to sign an agreement this week according to which Canada will read out and process ERTS data acquired at Canadian facilities. However, the power budget of the spacecraft and the time requirements for U.S. readouts must be taken into account when determining the amount of time which can be made available to foreign ground stations.

In view of the constraints on ERTS data acquisition, the fact that data collected will be available in any case, and the high cost of ground receivers, we cannot lightly encourage other countries to spend over $4 million for facilities to read out and process ERTS data. But neither do we discourage anyone from doing this. In fact, foreign stations would be the only source of international data if the video tape recorders should fail in the satellite. We merely suggest that other countries consider the facts of the situation carefully and then decide for themselves whether they wish in their own interest to make such investments at this time. Any which decide in the affirmative will of course receive all the necessary information we can give.

Question: Can the high cost of ERS ground receivers be reduced?

Answer: We are conducting research at NASA on high-power spacecraft systems which, if successful, could reduce the power requirements and therefore the cost of ground facilities. We are also investigating whether it would be feasible to use small APT-type receivers, such as are used to receive weather satellite data. This research will be reported generally as it yields results.

A final question: What happens after ERTS?

Answer: The ERTS project is designed to tell us what kind of a follow-on program should be devel-

oped, if any. Since the answers to this question will come with ERTS, we cannot yet relate future international participation or institutions to post-ERTS satellite programs.

A major question that I posed earlier related to the preparedness of nations to use the data we expect from ERTS and subsequent programs. A number of early and carefully considered steps have been taken by U.S. agencies to alert and prepare other countries to use Earth resources data when it does materialize. A basic activity has been extensive public discussion in a conscious effort to alert and educate the national and international communities to ERS prospects.

Ambassador Bush earlier recited a number of the initiatives that have been taken within the context of the United Nations. In addition, we have entered into cooperative programs directly with Brazil and Mexico to develop more immediate knowledge of this program, to train cadres from both countries, and to assist them in the development of unique ground truth sites of their own. We undertook to overfly those ground truth sites with Earth survey aircraft and provided the data to Mexico and Brazil. We are providing them with technical assistance in developing aircraft programs of their own, and we are extending this program to apply to satellite data as well as aircraft data. Representatives of these countries are here at the workshop to report to you on their experience.

Our resources in the aircraft program are too limited to permit broad extension of this type of cooperation to additional countries. However, we have acquired data in northern Argentina in support of a request from the International Biological Program. We have assisted India in the acquisition of infrared data over areas of coconut palm blight in Kerala State. We provided aircraft coverage last year over earthquake-damaged areas of Peru, to assist in damage assessment and redevelopment efforts. We are presently working with the Geological Survey of Jamaica and the Food and Agriculture Organization to acquire hydrologic information over Jamaica and surrounding waters. We hope that all of these aircraft remote sensing projects will help to demonstrate the utility of the technique to the international community.

I indicated earlier the cooperative agreement which we just completed with Canada. We also recently concluded an agreement with the Soviet Union to study the possibility of conducting coordinated air and space research over specified international waters and to exchange results of measurements made by each country over similar land sites in their respective territories. The purpose of this agreement is to advance space and conventional survey techniques for investigating the natural environment.

We are attempting to meet other international interests by opening our facilities to visits by foreign delegations, by circulating information on the program, and by extending the NASA international university fellowship program to cover Earth resources curricula in seven leading U.S. universities.

I think you will be particularly interested in the response we have received to our general invitation to the world community to submit proposals for the analysis of ERTS data, as well as data which is to be collected by means of the Earth Resources Experiment Package, or EREP, which will be flown in the U.S. Skylab program. To date, we have received 60 proposals from 25 foreign countries. The following is a list of the countries from which proposals have been received:

Argentina	India
Australia	Indonesia
Belgium	Israel
Bolivia	Japan
Brazil	Korea
Canada	Netherlands
Chile	Norway
Colombia	Peru
Ecuador	Sweden
France	Switzerland
Germany	United Kingdom
Greece	Venezuela
Guatemala	

Let us assume for a moment that the ERS program is validated and that we move on to an operational system. How can we imagine such a system in terms of its international operation and how it could serve the international community of users? I think it is reasonable to expect that the United States, and perhaps the Soviet Union and other nations, will have continuing interest in the operation of an Earth resources survey satellite

system to meet their own national needs. If such systems existed, it would be an economic matter to acquire global coverage at the same time that national coverage is acquired. The fundamental need, then, is really for a mechanism for the international dissemination of data and for assistance in its interpretation.

In various public statements, in the UN and elsewhere, we have suggested very briefly the kind of arrangement we imagine might serve these purposes. The nations may at some appropriate time want to consider setting up a UN facility—not a new agency but a facility—to serve member States of the UN and to serve the existing specialized agencies and other international agencies which already use resources data for development applications. Such a facility would need to include special computer and data analysis capabilities to service the wide needs of the specialized agencies for resource data. The approach could be relatively economical. Furthermore, the facility would insure the open and central international processing of the data. It would involve the resources people who already have established relationships through the Agency for International Development (AID). This AID aspect, of course, must be closely related to the extent that the less developed countries are involved. Certainly, there would seem to be no need to duplicate the work of the FAO, the WHO, the UN Resources and Transport Division, and so on. As for the cost, it is too early to determine what this might be. It is my personal view that it would be extremely difficult to establish a cost-benefit ratio between Earth resources *data* which a country may receive and the *benefit* the country may or may not derive from that data. Therefore, I don't suggest any cost-benefit or fee basis at all, but rather a simple arrangement in which the UN facility would acquire, at cost, copies of the data, and would duplicate data that the U.S. and other countries acquire through space segments. They would then provide the data directly to the AID groups and the users. Some basis for cost sharing might emerge at a later time.

In summary, we are at a point where we have experiments and expectations. We do not yet have an established international service, and we do not have a clearly demonstrated validity. The first major test will be ERTS-A. We look upon this workshop as one means of assuring, through international understanding and participation, that ERTS-A and its successors will be widely tested, considered, and evaluated as part of the general preparation of peoples everywhere to use the new technology for our mutual benefit.

SESSION II

Chairman: Ned D. Bayley

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Aerospace Methods of Revealing and Evaluating Earth Resources

WILLIAM A. FISCHER
EROS Program Manager
U.S. Geological Survey

The data to be derived from the ERTS satellites are intended to contain as few variables as possible so that the data will be easily usable by large numbers of Earth scientists and technicians. The reduction in variables results from the use of very narrow-angle viewing systems and selection of an optimum Sun-synchronous orbit. Resulting images will be nearly orthographic (map-like) upon collection and, with proper processing, will have a high uniformity of illumination so that objects having similar reflectance characteristics will appear similar throughout the image. Parts of the spectrum to be recorded by the sensors aboard ERTS were carefully selected to provide the kinds of information needed by many Earth scientists and resource managers. This information includes water distribution, vegetation distribution, snow distribution, gross cultural feature distribution, and the distribution of suspended sediment in water. The ERTS system provides repetitive data so that changes in this distribution with time may be easily detected.

This paper is intended to provide insight into the design rationale for the NASA Earth Resources Technology Satellites (ERTS) and to describe user agency information needs and progress in information extraction. It is hoped that an understanding of the rationale used in the design of ERTS will assist you in designing appropriate and meaningful experiments with ERTS data.

To avoid any semantic misunderstandings, I would like to begin with a review of terms.

ERTS is a NASA unmanned satellite program that will place two satellites in orbit, the first (ERTS-A) in early 1972. NASA will collect the data, process it to remove all systematic errors, and make it available to federal agencies and selected experimenters.

Skylab is a manned laboratory, to be launched in late 1972. It is designed primarily for astronomical observations, but will also carry an Earth Resources Experiment Package (EREP). Skylab is expected to yield limited quantities of highly experimental data.

EROS (*E*arth *R*esources *O*bservation *S*ystems) is a program of the Department of the Interior to acquire, process, and utilize data from both aircraft and spacecraft. We consider the data from ERTS to be the principal experimental input to the EROS program. The EROS program will test ERTS, Skylab, and aircraft data for operational use.

Repetitive data is the term used for similar data collected on a regular schedule. This kind of data facilitates mapping of changes and trends, and aids in identification. The methods of recognizing a willow tree form an example of the use of repetitive data for identification. One may recognize a willow tree by close examination of the leaf or bark; this approach requires very high-resolution observations. One may also observe the tree from an aircraft and note the characteristic dip in the crown; this approach also requires very high-resolution data. One may also observe the distinct yellow-green color of the willow tree and thus identify it; this method requires a multispectral approach, but resolution requirements are less stringent. One may also recog-

nize the willow tree by knowing that it turns green before other deciduous trees and observing it at the proper time. The resolution requirements for this approach are also less than needed for approaches involving analyses of shapes.

A study of Interior Department activities undertaken by the Westinghouse Corporation showed that the benefits to be derived from repetitive data diminish greatly if the period between repetitive observations exceeds 30 days.

Cartography and mapping. Under the EROS program, we accord a broader definition of responsibility to the fields of cartography and mapping than is common. In addition to producing topographic or planimetric base maps, we define cartography as including the preparation of maps of given themes or resources, such as maps showing the distribution of surface water and its change with time. Statistical information relating to these themes is also considered to be a cartographic product.

National map accuracy standards are United States standards used to control the precision of both plan positions and altitude measurements. The national map accuracy standard for planimetric maps requires that 90 percent of all features appearing on the map must be located within 1/50 of an inch (approximately 0.5 mm) of correct position at map scale.

Plane coordinate systems are systems of rectilinear coordinates that enable an investigator to accurately determine map locations with simple measuring devices under field conditions. Plane coordinate locations may be easily converted to geographic coordinate locations. The Universal Transverse Mercator plane coordinate system has been adopted for use in the ERTS and EROS programs.

ERTS DESIGN RATIONALE

Recognizing that economic benefits accrue only when information is applied in a decision process, a review of decision models within the Department of the Interior was undertaken. This review led to the identification of 18 informational needs, which ultimately led to the design of the ERTS.

It became evident at the onset that the most serious need was for data at regional scales, herein defined as 1:250 000 or smaller. Both regional (small-scale) and local (large-scale) maps are needed, each serving its unique purpose. Data collected and presented at regional scales facilitates the top-down decision flow that is becoming more important today as we attempt to relate our scientific and technical resources data to the overall environmental situation. The review of decision models revealed that much detailed information is lost to resource managers because it is not timely or is not developed on the basis of their needs.

An example of the decision models analyzed in this study is that of decisions to lease rangelands belonging to American Indian tribes. Because lease revenues provide the Indian nations with a large part of their income, optimum utilization of rangelands is essential for their economic growth. All money derived from these leases reverts to the Indian nations. In this model, soil and range inventories are utilized in reaching the decision to lease, and a series of utilization checks is employed to review results of the decision and improve subsequent decisions. Information currently used in the soil/range inventories is shown in figure 1. It was noted

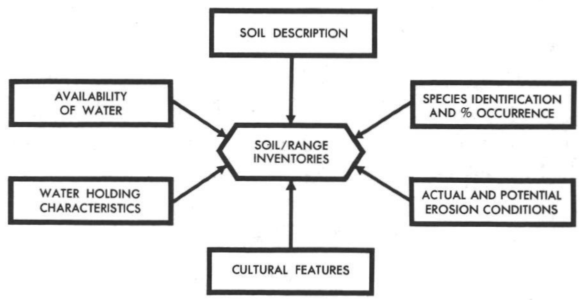


FIGURE 1. Inputs employed for soil/range inventories.

that there is no requirement for a continuing inventory of forage grass distribution and vigor. This obviously useful information was not identified because no means existed for timely collection of appropriate data. The decision process is illustrated in figure 2. In each decision model, the requisite information was noted, and additions such as forage grass distribution and vigor were made, based on scientific knowledge of the potential capabilities of remote sensor surveys. The possibility of substituting observations for those requested was also considered; for example, water-holding characteristics of soils are difficult to determine from airborne or spaceborne observation points. However, this char-

acteristic is reflected in the vigor of the forage grasses that grow upon them. Accordingly, observations of vigor of forage grasses were recommended substitutes for the requisite information. Utilization checks consisted of a statistical check of vegetation presence and vigor, evidence of overgrazing or undergrazing, and economic analyses. Data for all utilization checks, save economic analysis, can be provided from remote platforms.

Information requirements thus identified were summed and equated against the known capabilities of remote sensing systems.

Both aircraft and spacecraft were considered as acquisition vehicles, and it was noted that each platform has unique advantages. Spacecraft, in contrast to aircraft, can (1) provide rapid coverage of very large areas, (2) provide repetitive coverage at constantly diminishing costs, (3) adhere closely to acquisition schedules, (4) economically utilize narrow-angle viewing systems, and (5) transmit data directly from great distances to recognition processing centers. Aircraft, in contrast to spacecraft, can (1) be dispatched quickly to meet a given need, (2) provide various levels of resolution with the same sensors, and (3) return film quickly for processing and analysis.

This capabilities analysis led to the design of a data collection system that involves both spacecraft

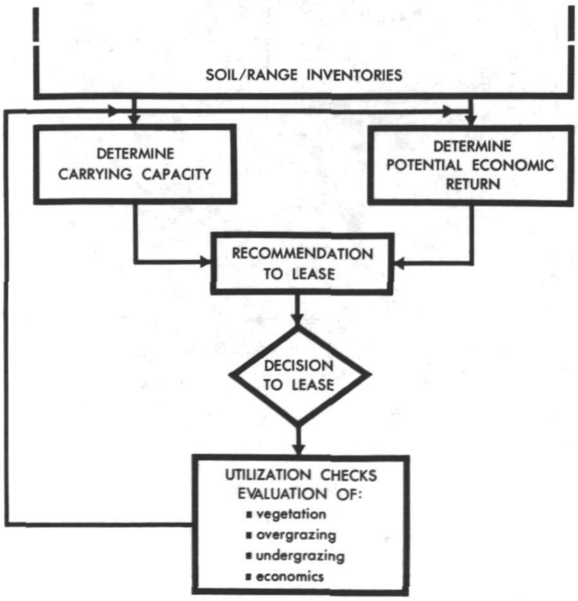


FIGURE 2. Decision process used to determine whether to lease specific areas of Indian rangeland to the public.

and aircraft applied in a supportive manner. In most cases, heaviest dependence is placed on spacecraft data supported by aircraft; but in some areas, such as aeromagnetic and topographic surveying, aircraft remain the prime data-gathering system that will be supported by spacecraft data in the future. The principal reasons for adopting spacecraft as prime collection vehicles for most surveys are illustrated in figures 3, 4, and 5. Figure 3 compares narrow-angle space photography to wide-angle photography acquired from aircraft. Narrow-angle systems have three basic advantages:

(1) They facilitate identification by showing features at essentially the same angular perspective, in contrast to wide-angle photography that shows features at various perspectives. For example, in a wide-angle photograph of a forest one sees the tops of some trees and the sides of many trees. Sides of trees and tops of trees look quite different; as a result, similar types of vegetation appear dissimilar in wide-angle photographs. Conversely, narrow-angle systems see essentially only tops of trees, and trees that are alike look alike.

(2) The straight-down view aids penetration of forests and water.

(3) Narrow-angle systems permit collection of data that are essentially orthographic upon collection. Figure 4 shows the path of a power line as it appears on the edge of a wide-angle photograph (top) and as it appears looking straight down within a narrow cone of rays (bottom). The power line is straight on the ground, and its shape and alinement are better shown in the narrow-angle view. This quality facilitates rapid conversion of narrow-angle data into map form and aids interpretation by showing features in their true shapes.

Figure 5 is a mosaic of aerial photographs of a part of Saudi-Arabia. All pictures were acquired and processed with the same system; there was, however, a difference in time of acquisition. Approximately three hours separated the north-trending flights from the south-trending flights. The areas outlined with dashed lines are homogeneous, yet they exhibit apparent differences because of change in the illumination angle of the Sun. A synoptic image acquired from space would show all of the area in this mosaic and more, and terrains that are alike would look alike. Additionally, acquisition of space images can be much more pre-

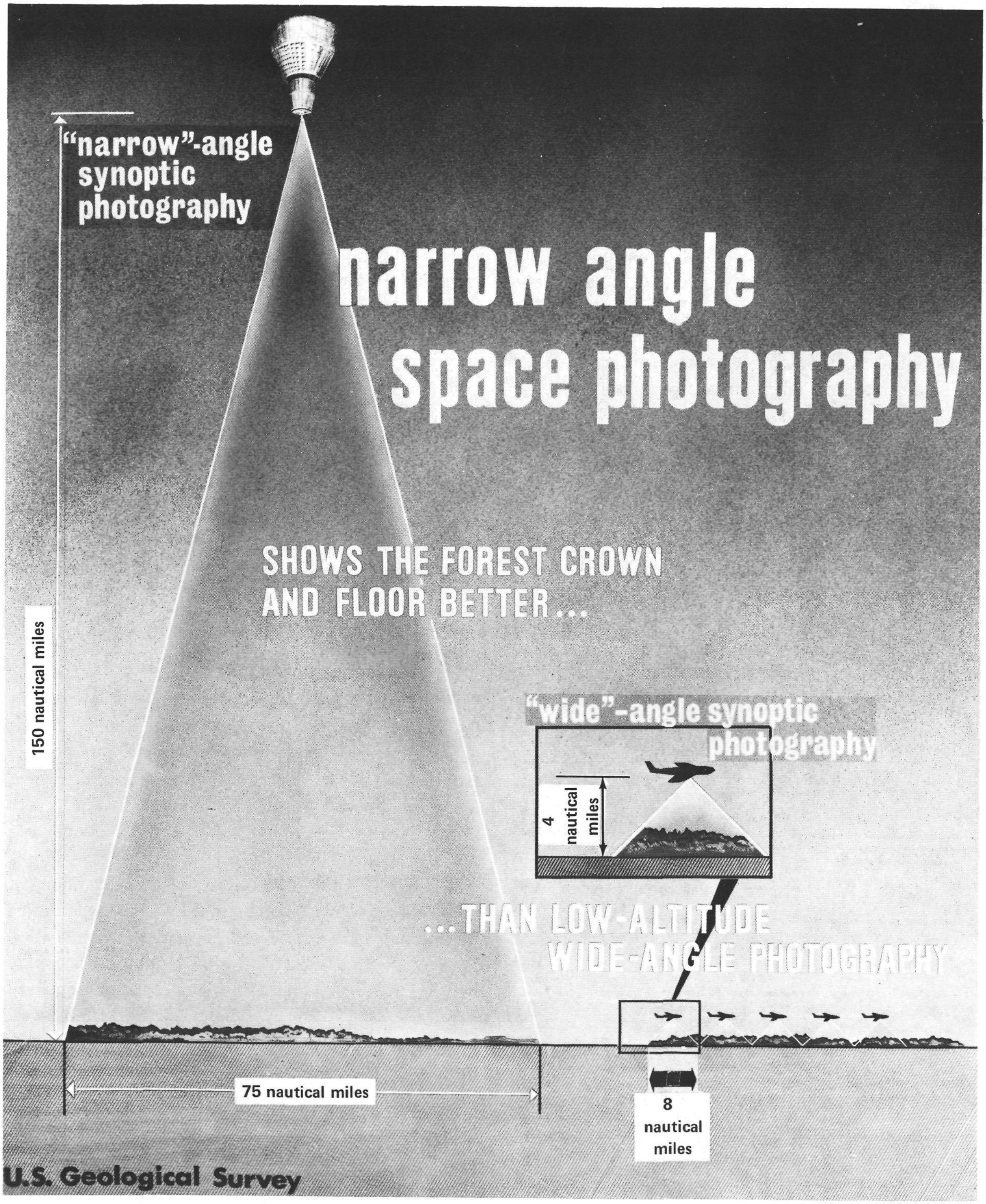


FIGURE 3. Space photography compared to aerial photography.

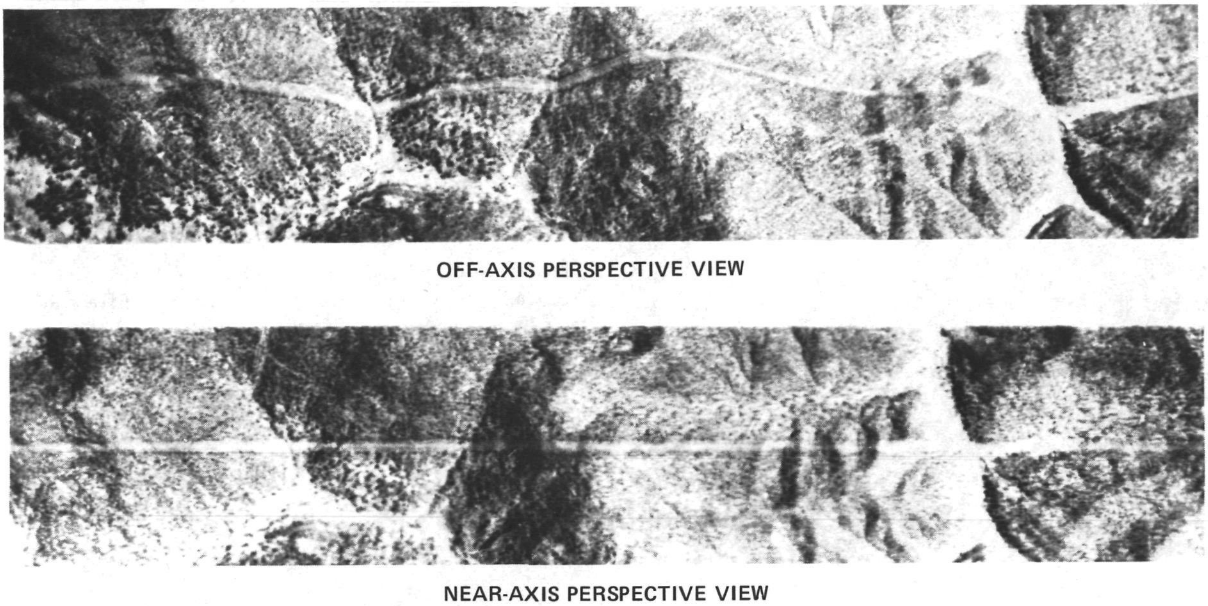


FIGURE 4. Effects of perspective angle on relief displacement.

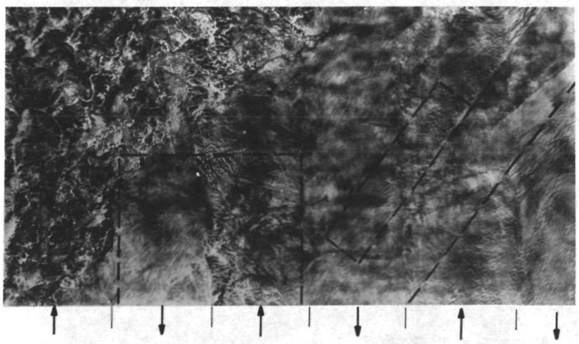


FIGURE 5. Apparent terrain differences in photomosaics may not represent actual differences. (Arrows show direction of flight.) Areas within dashed lines are known to be homogeneous.

cisely scheduled than aircraft images. Thus space images can be acquired at optimum times.

The analysis of information needs and systems capabilities led directly to the selection of the multispectral characteristics and sensors of the ERTS system. Figure 6 shows a color infrared and three black-and-white space photographs of a part of the Imperial Valley of California. The black-and-white images are similar to those that will be transmitted from the ERTS spacecraft. Each black-and-white image records energy in a different part of the spectrum; one records green light, one records red light, and the other records energy in the invisible infrared. The green band was selected to see through water for observations of subaqueous landforms; it is also a near-optimum band for discriminating rocks and soils in arid environments. The red band was selected for discrimination of cultural features against a vegetated background; this band is also useful for identifying crops. The infrared band, just beyond the visible spectrum, was selected to show landforms, vigorous vegetation, and water. The black-and-white images may be combined into a color composite, such as that shown at the top of figure 6. In such a composite picture, water is black, vigorous vegetation is red, and suspended sediment and bottom features are blue.

These photographs are part of an experiment undertaken during the flight of Apollo 9 to test the use of these bands for observing the Earth from space. The results demonstrated that multispectral techniques aided in identifications and in structuring the information upon collection, so that extraction of information from the data was facilitated.

Figure 7 shows two comparative views of Atlanta, Georgia and vicinity taken simultaneously from Apollo 9. The red band was selected to show cultural features; the photograph on the right, taken with red light, shows the city of Atlanta, together with related road networks. In the image on the left, made in the infrared band, Atlanta is barely visible, but the landforms, lakes, and reservoirs are clearly discernible.

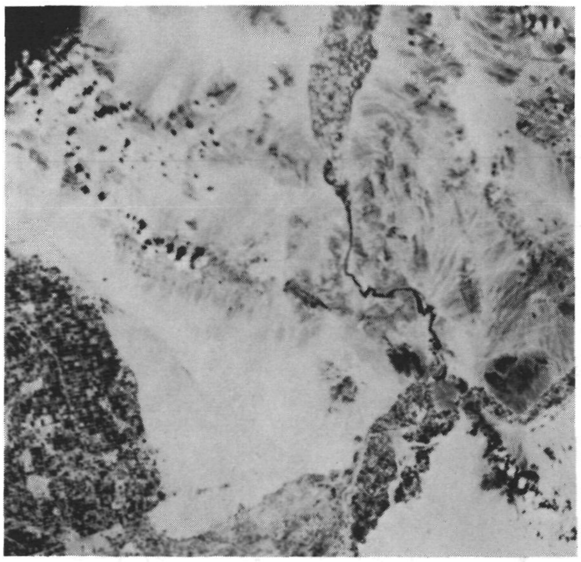
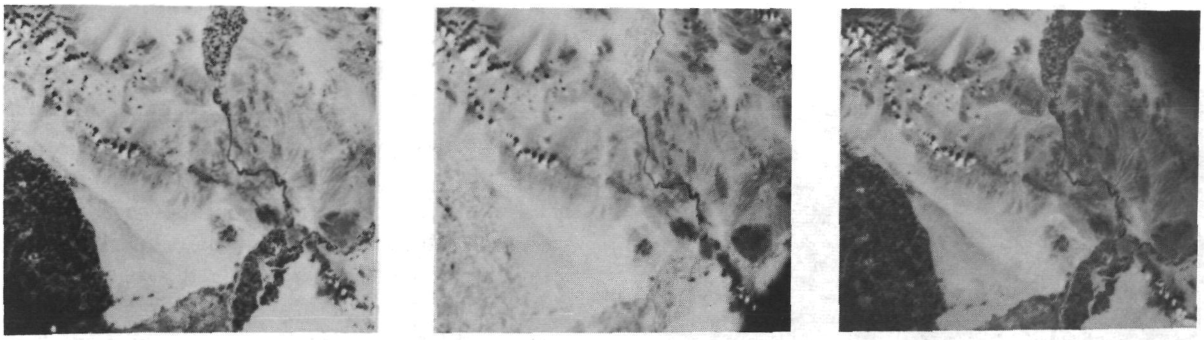


FIGURE 6. Multispectral view of Imperial Valley, California, produced with four separate cameras using different films to bring out cultural features, vegetation, water, and land features.



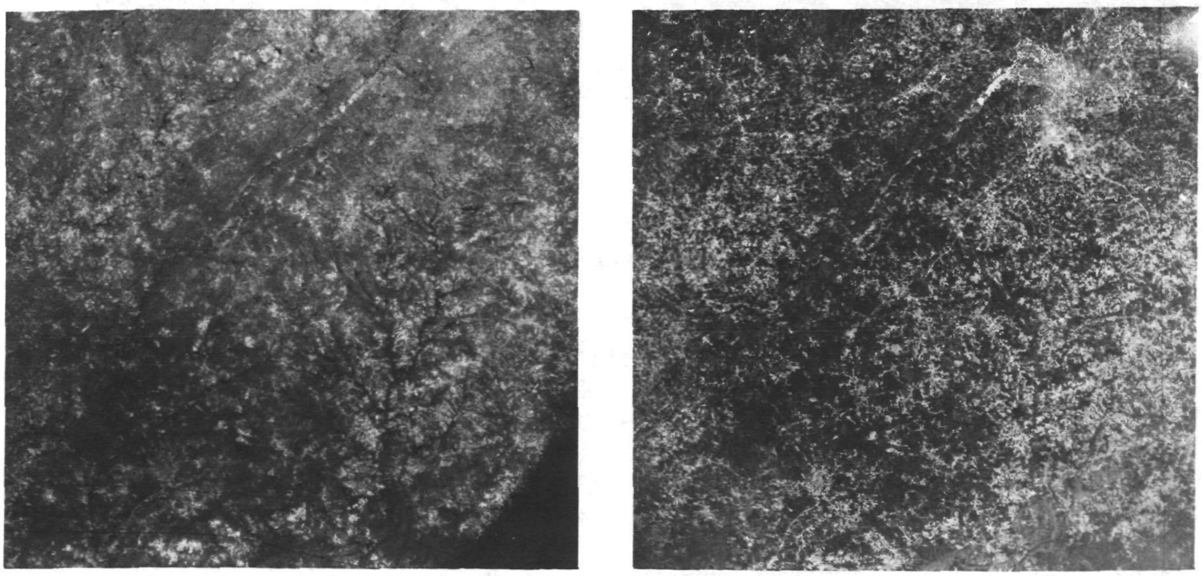


FIGURE 7. Simultaneous space photos of Atlanta area taken in infrared (left) and visible red light.

RESULTS OF INFORMATION NEED ANALYSES AND PROGRESS IN INFORMATION EXTRACTION

The following paragraphs enumerate the information needs identified in our analysis of decision models and illustrate progress to date in developing methods for interpreting or routinely extracting resources and environmental information. The needs are divided into those related to land, water, vegetation, cultural features, and geophysical information.

Land Information Needs

First among the requirements for timely information about our lands is small-scale planimetric maps. Tests were undertaken, utilizing photography acquired during flights of the Apollo and Gemini spacecraft, to test the utility of space photographs for making regional-scale photoimage maps. Our first product was a 1:1 000 000-scale maplike photoimage mosaic of approximately 500 000 square kilometers of Peru, Bolivia, and Chile, assembled from a series of more-or-less random photographs taken by astronauts Cernan and White. Copies of the mosaic were sent to the President of Peru, who commented favorably on its usefulness and objectivity.

More recently, an existing 1:250 000-scale line map was combined with parts of two Apollo photographs to produce a composite line and photoimage quadrangle map of part of the state of Arizona. Figure 8 shows the composite map; figure 9 compares a part of the composite map with the conventional line map. Close inspection reveals that the composite map has a much higher information content than either the images or the conventional line map alone. These tests also showed that space photography can be used to update existing regional maps, as shown in figure 10, and demonstrated that photographic imagery acquired with relatively narrow-angle systems is essentially orthographic upon collection. The photographs meet or exceed national map accuracy standards for planimetric positioning at scales of 1:250 000 and smaller. We believe that the ERTS data, when properly processed, will have similar geometric fidelity. The combined line and photoimage map (figures 8 and 9) has a very fine grid superimposed on it. The grid is the Universal Transverse Mercator plane coordinate system that has been adopted for use in the ERTS program. Information concerning this grid and methods of determining positions from it can be obtained by writing to the U.S. Geological Survey.

Additional land information needs are:

(1) Landform classifications. Research using radar images has shown that uniform, small-scale images facilitate classification of landforms. Landforms thus classified can be related to land productivity, average income, and engineering and construction costs.

(2) Land use information. Land use maps have been prepared of urban and rural areas in the United States using space photography.

(3) Geologic structural information. Knowledge of geologic structures can assist in mineral and water explorations. Many previously unmapped structures are visible in space photography.

(4) Subaqueous landforms. Images showing landforms beneath the water can aid marine geological exploration. Space photography is unique in its ability to penetrate water to significant depths. Some Apollo and Gemini photographs have shown bottom features to depths of 50 meters or more (figure 11).

(5) Topographic information. There is a worldwide need for topographic maps. At the present time, aircraft systems must still be employed to supply this information; topography cannot be mapped from ERTS or Skylab data.

Water Information Needs

Water information needs include soil moisture distribution, suspended sediment distribution, wetlands distribution, and the distribution of surface water and snow. Although soil moisture is not directly interpretable from the ERTS data, relative soil moisture distributions can be interpreted from local differences in albedo and/or effects on overlying vegetation. Figure 12 shows an area of high soil moisture content, the track of a thunderstorm in the southwestern United States. Other water information needs include distribution of snow and water content of snow. The distribution of snow will be visible on ERTS images, but the ERTS system will not provide measurements of water content of snow. Research utilizing ground microwave systems for measuring water content is in progress, and Skylab will carry a microwave radiometer system to provide experimental space data that may

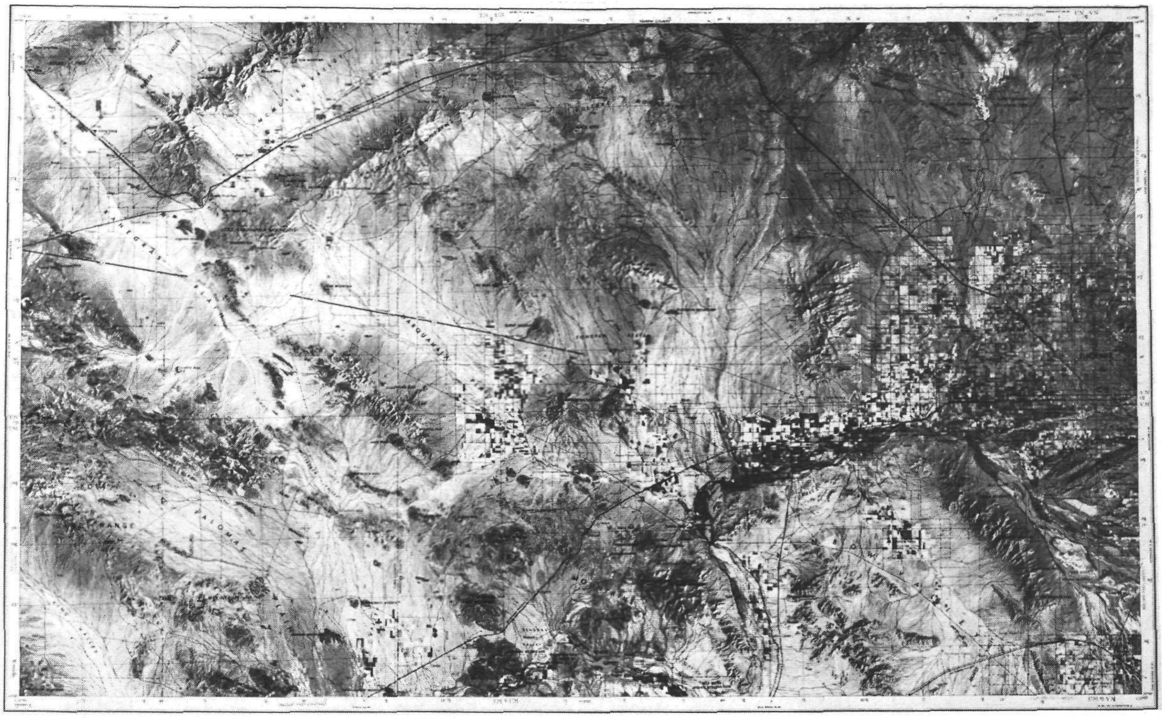


FIGURE 8. Conventional line map of Phoenix area combined with space photographs to give improved accuracy and detail.

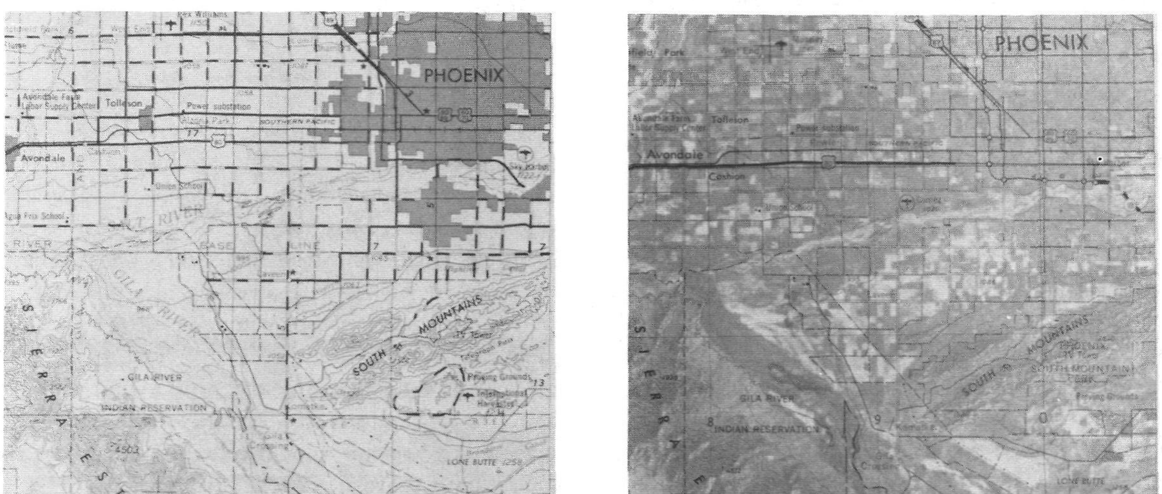


FIGURE 9. Composite map compared with conventional line map.

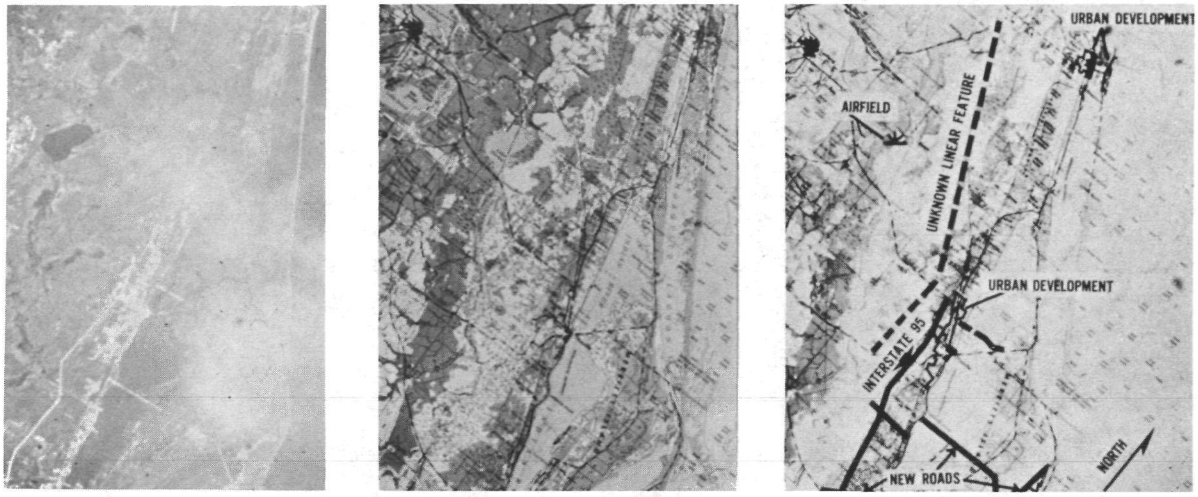


FIGURE 10. New construction identified in Gemini 7 photography illustrates usefulness in updating base maps.

FIGURE 11. Space photo showing subaqueous landform in Caribbean Sea.

FIGURE 12. High soil moisture area apparent in Gemini color photo of Midland-Odessa, Texas.

lead to a future capability to measure water content of snow. Technology exists for mapping the distribution of water and snow automatically, as shown in figures 13 and 14. In the map shown in figure 14, areas of thin snow appear in green; thick snow is shown in blue; and the areas that have no snow are white.

Enhancement techniques exist for showing the distribution of sediment in near-shore areas (figure 15). This information is interpretable in terms of the dynamics of water body disturbances, natural and manmade, that are adding to the sediment load. As shown in figure 16, this information is useful for improving the efficiency of the shrimping industry.

Vegetation Information Needs

Vegetation information needs include (1) the distribution of natural vegetation, (2) the distribution of agricultural vegetation, and (3) the distribution of vegetation in vigorous growth. We expect

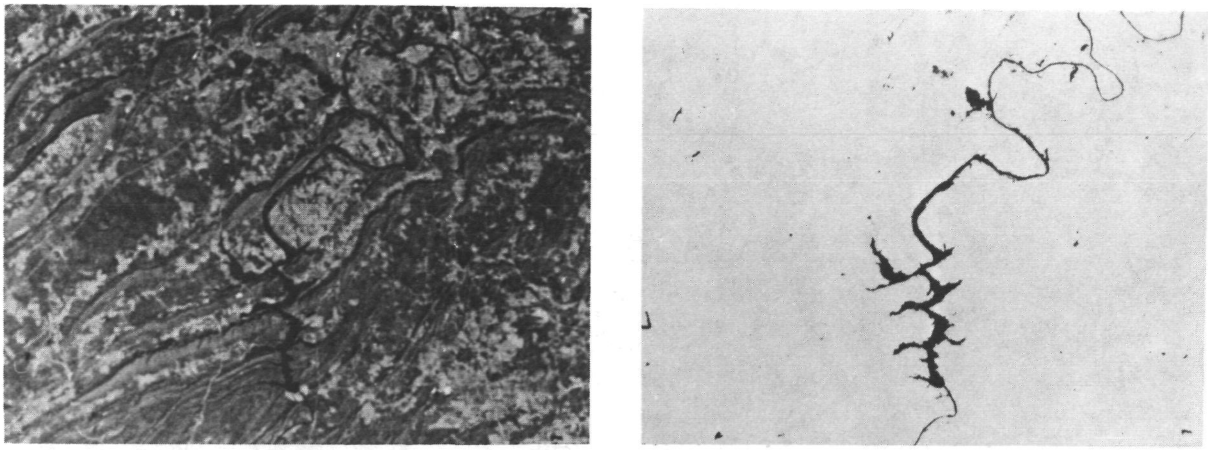


FIGURE 13. Automatic mapping of surface water area. The water map (right) was automatically extracted from the image at left (an infrared space photo of a portion of northern Alabama).

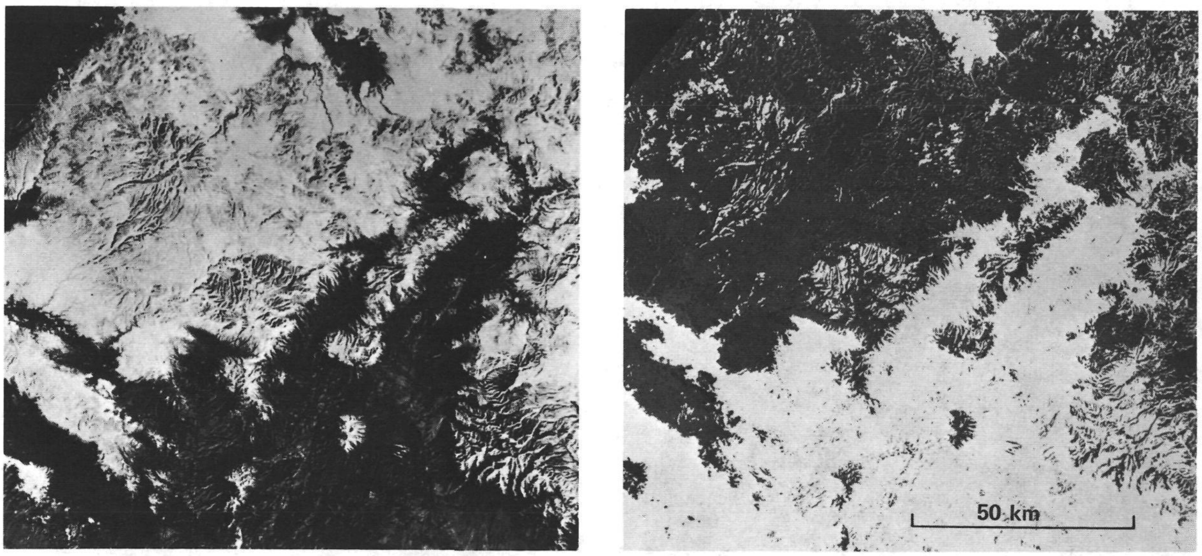


FIGURE 14. Automated snow mapping. At right is a color-coded map produced from the Apollo 9 infrared photo of an Arizona snow scene shown at left.

that all three of these information needs will be wholly or partially met with the ERTS system, supplemented by selective aircraft observations. The technology exists to automatically map the distribution of vegetation, as shown in figure 17. It is anticipated that observation of the geometric field patterns and/or more selective discrimination of reflectance characteristics may permit automatic separation of natural vegetation from agricultural vegetation.

Cultural Features Information Needs

Needed information relating to cultural features is shown in figure 18. These needs include city outlines, major transportation networks, and classes of cultural and natural features within the urban scene. City outlines show with remarkable clarity in Gemini and Apollo photographs. Comparison of outlines seen on space photographs with outlines drawn on older maps has resulted in maps that show direction and rate of urban growth. Our geographers are

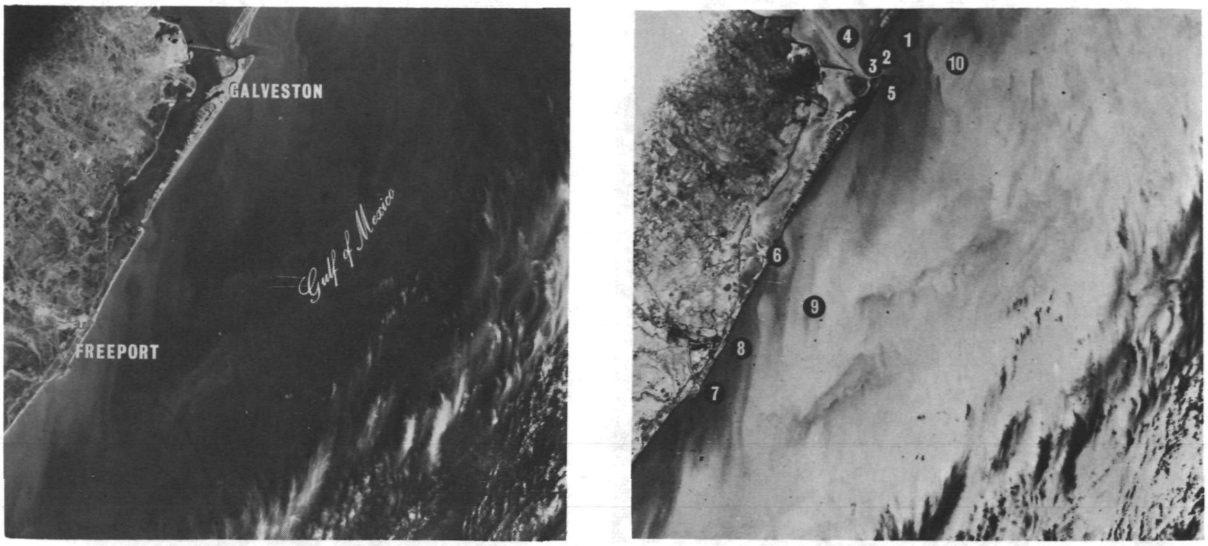


FIGURE 15. Automatic mapping of near-shore features. Image at right is negative of Apollo 9 space photo shown at left. Numbers on negative indicate locations where color measurements were made on original transparency.

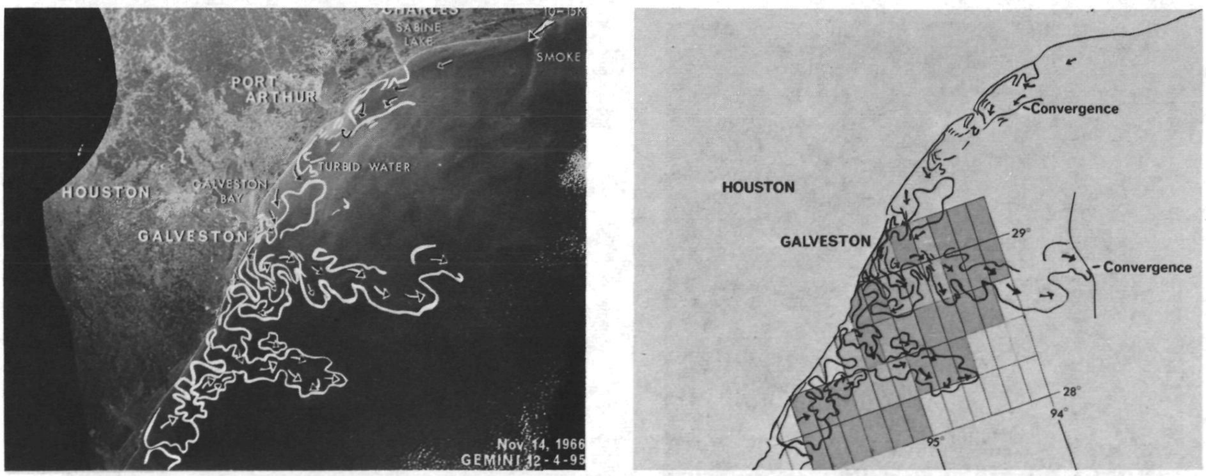


FIGURE 16. Space photography used to help shrimp industry. Outline of turbid water is shown on Gemini photo at left. Map at right shows distribution of fishing vessels in same area by color coding.

having success in evolving regional factors which, when multiplied by the area of urban growth, result in estimates of population increase. Current investigations are attempting to routinely extract classes of information from within urban areas. One class of information, for example, consists of buildings, roads, and parking lots; these are all impervious surfaces. Such information can be useful in determining water runoff rates. In the upper left of figure 19 is an aerial photograph of an area near Falls Church, Virginia; along the bottom are the four classes of information automatically extracted from within that scene. We have not as yet attempted to make similar analyses of space photographs.

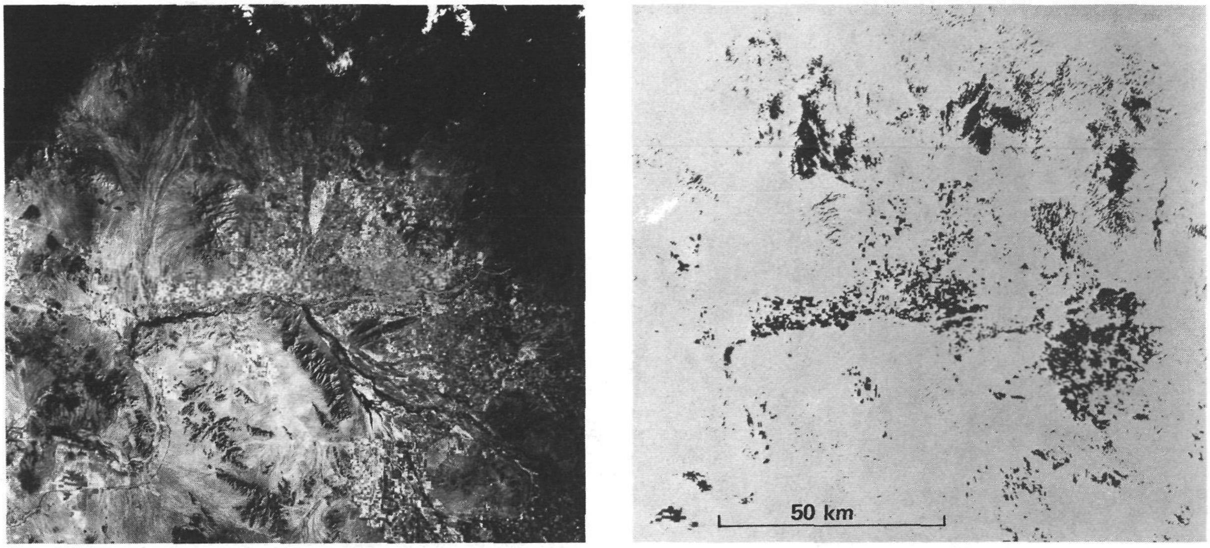
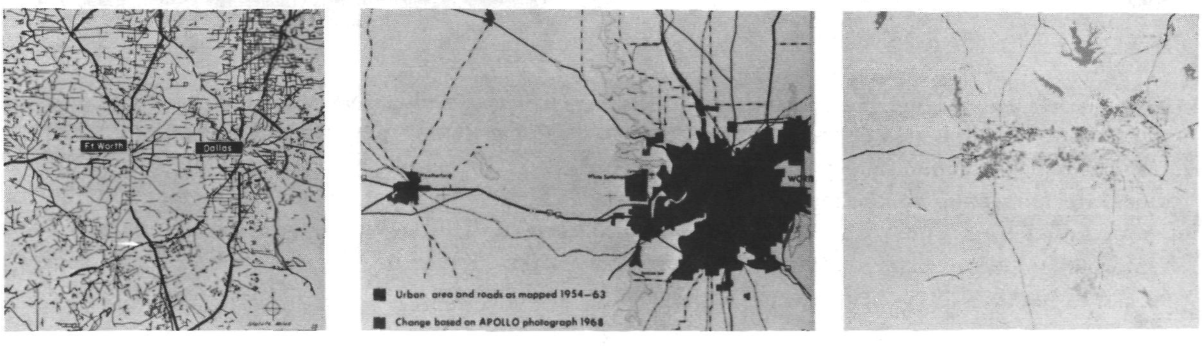


FIGURE 17. Automated vegetation mapping. Map on right shows IR-reflective vegetation extracted from Apollo 9 IR photo of Phoenix shown at left.

FIGURE 18. Maps of cultural features produced from Apollo 6 color photo (left) of Dallas-Fort Worth area. Map at lower left shows roads throughout area; center map shows changes in roads and urban areas; major roadways, urban areas, and bodies of water are indicated by three distinct colors in map at right.



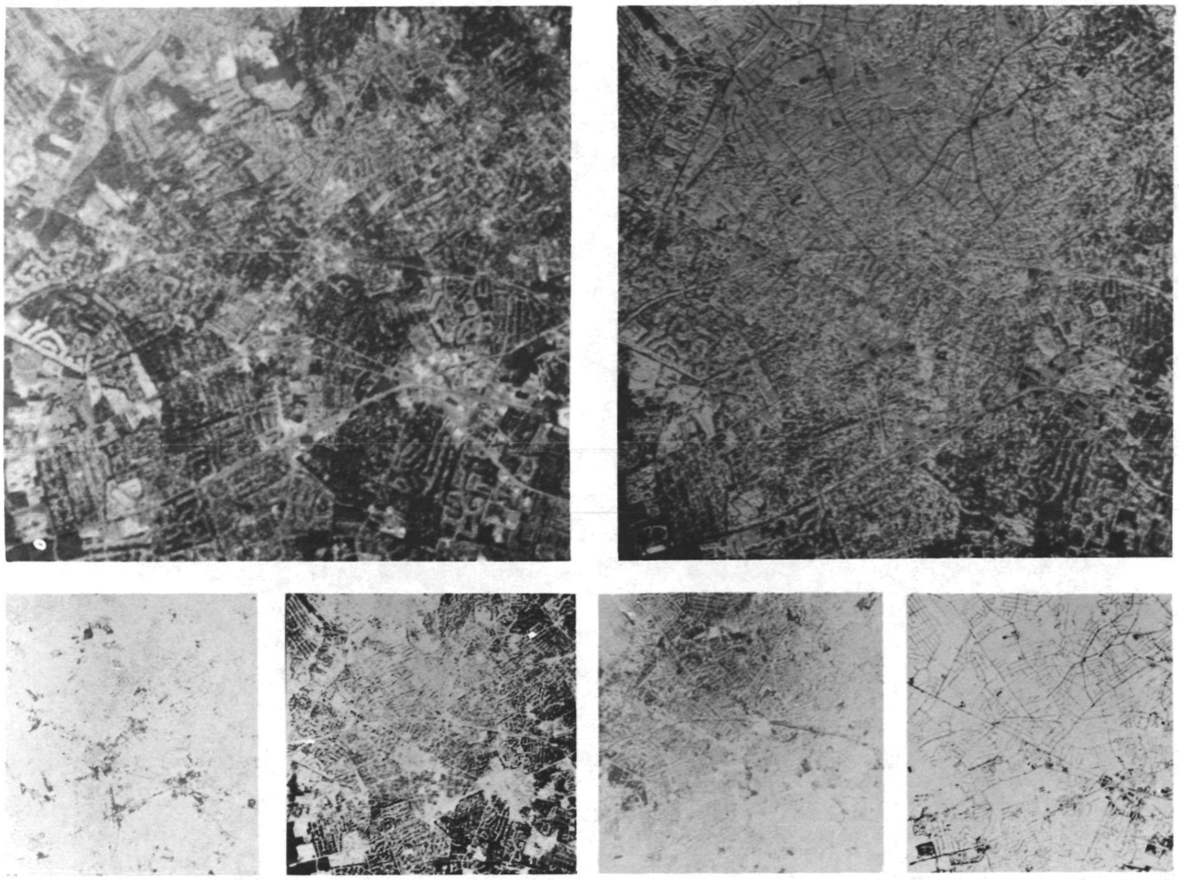


FIGURE 19. Automatic data extraction. From color IR aerial photo (top left), four types of data were extracted by density slicing process: (a) rooftops, excavations, and water; (b) trees; (c) grass; (d) roads and parking lots. Composite print (top right) was made from separation negatives (a) thru (d).

CHANGE DETECTION

The most important information sought from the ERTS data is change in all of the aforementioned types of information, e.g., the change in snow distributions and city outlines with time. Because of the near-orthography and the time synchronism of the ERTS data, sequential coverages may be easily compared and changes may be detected and mapped.

Figure 20 shows two space photographs of the Dallas-Forth Worth area of Texas; they were taken about one year apart. Figure 21 shows a map of the southeastern part of Dallas in which all the changes recorded in figure 20 are shown as bright dots. Many changes have been detected but not identified.

Figure 22 shows aerial photographs taken at approximately the same times as the space photographs for change identification purposes. The change marked C represents a change in the water level of a reservoir; other changes are buildings constructed in the time interval between coverages. It is worthy of note that, although the optical resolution of the space photographs was probably no better than 200 meters, new buildings approximately 70 meters on a side were detected.

GEOPHYSICAL INFORMATION

Two types of geophysical information needs were identified, namely thermal and magnetic. Geothermal data, such as shown in figure 23, can be acquired from ERTS-B but not ERTS-A. Magnetic data generously provided by our Soviet colleagues are to be reduced to map form, as shown in figure 24, and geologically interpreted.

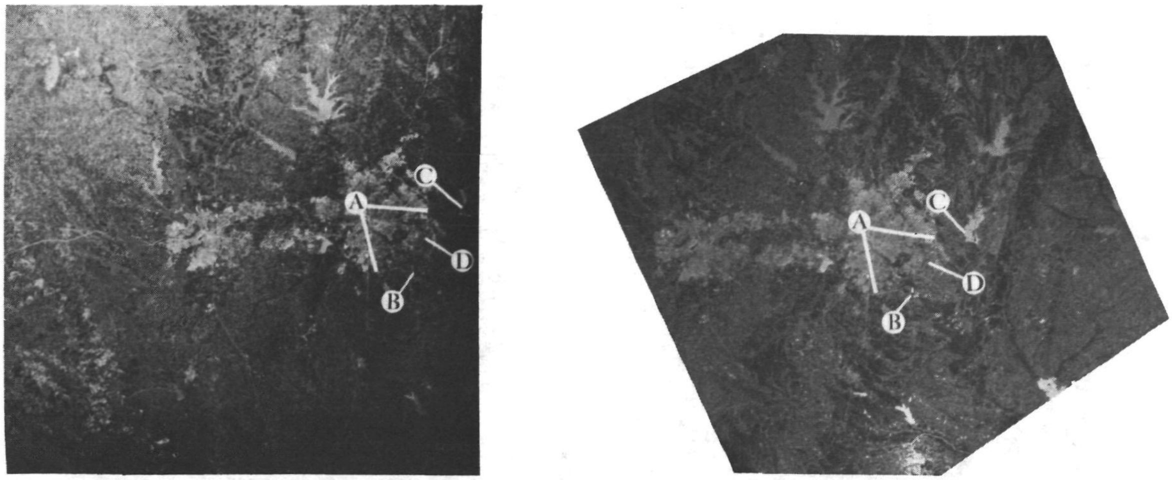


FIGURE 20. Two photos of Dallas-Fort Worth area taken from Apollos 6 and 9, nearly a year apart, show various changes.

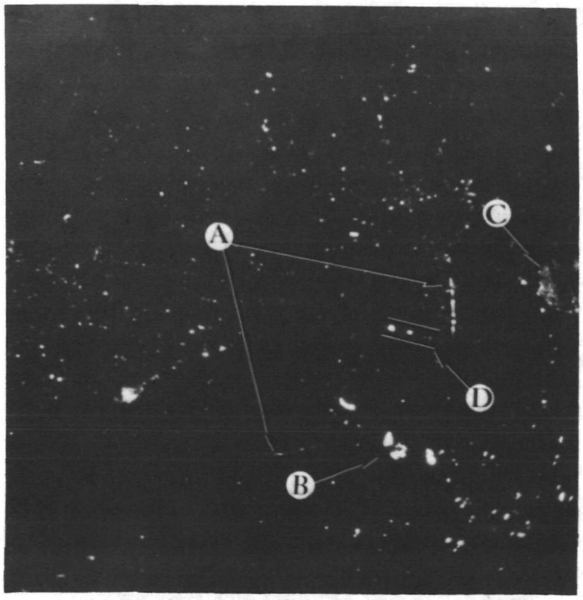


FIGURE 21. Changes detected between sequential photos of figure 20: A=freeways; B=artificial lake; C=water-level changes; D=new buildings.

ENVIRONMENTAL MONITORING

Provision of the information discussed in this paper, together with rates of change in the character or distribution of these information elements, will be a major step toward supplying data needed for an environmental monitoring system.

Many of the parameters used to define pollution or environmental quality cannot yet be monitored from remote positions. However, research efforts that may lead to this capability are producing encouraging results. In some cases, secondary effects may be observed that are meaningful. Figure 25 is an aerial color infrared photograph of the Potomac River. The red streaks in the river are algae that result from pollutants discharged upstream. We plan to begin studies this summer that will attempt to relate algae distributions with *in situ* water-quality measurements in order to develop a model for interpreting observations of this kind.

Our studies include analyses of patterns of development in various environments in an effort to

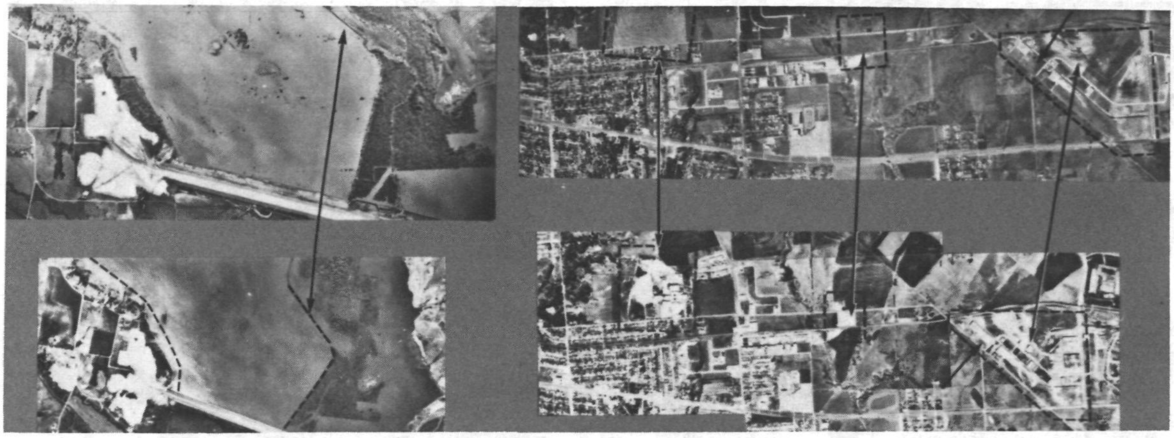


FIGURE 22. Verification of changes by aerial photography. Left pair of photos shows water changes; right pair shows construction changes (areas C and D of figures 20 and 21).

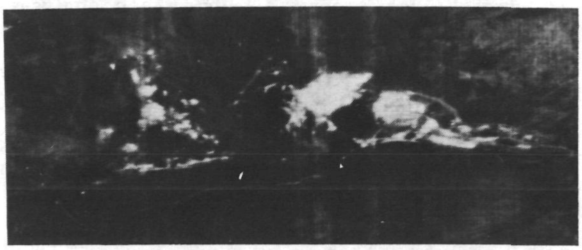


FIGURE 23. Thermal structure of surface: IR imagery of The Geysers geothermal steam field, California.

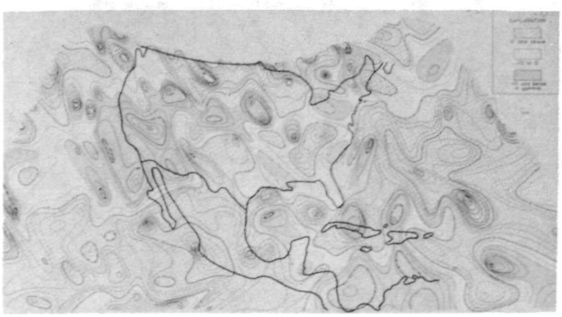


FIGURE 24. Crustal magnetic anomalies: magnetic map contoured from data taken by U.S.S.R. satellite Cosmos 49.

FIGURE 25. Aerial color IR photo of Potomac River shows algae, an indicator of pollution.

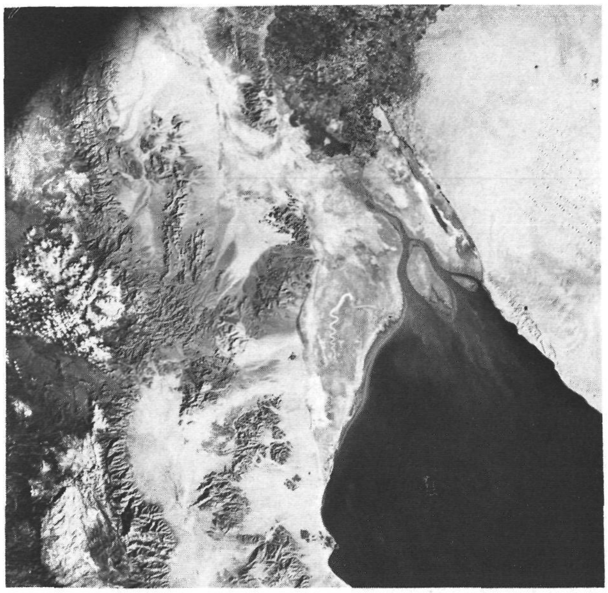


FIGURE 26. Apollo 9 color IR photo of Colorado River delta.

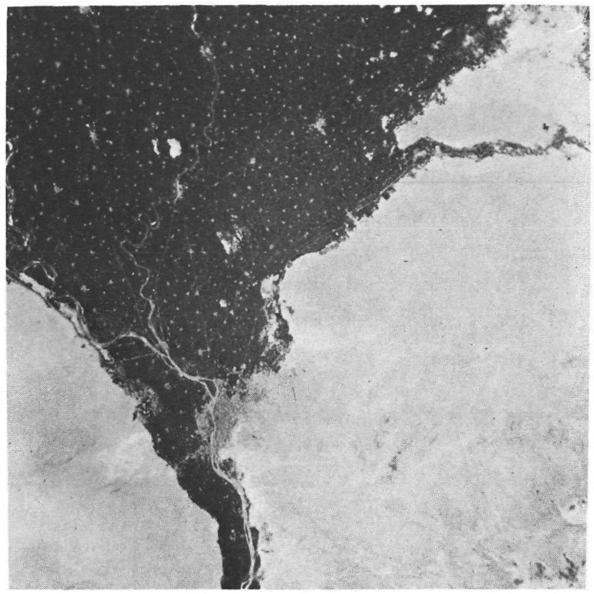


FIGURE 27. Nile River delta from Gemini.

arrive at a better understanding of development constraints and thrusts. Figure 26 shows the relatively undeveloped delta of the Colorado River; the general physiographic and environmental setting is quite similar to that of the highly developed Nile delta, shown in figure 27.

Geographers have analyzed this photograph of the Nile delta in an attempt to verify or deny their "central place" theory. Results of their analyses are not conclusive, but one clear fact emerged: The space photograph presented more objective geographic information than any map of the region, thus making the photograph of high educational value. I think we will find that the educational values of space data will exceed all other values derived from this and succeeding experiments.

Remote Sensing in Geology, Hydrology, and Geography

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Remote sensing from satellites and aircraft has many applications to the scientific disciplines of geology, hydrology, and geography. The feasibility of remote sensing for geologic purposes has been demonstrated by the discovery of significant areas for mineral exploration in the Southwestern United States from space photographs, the delineation of rock structures favorable for oil and gas exploration, and the description of changes in landforms caused by geologic events such as volcanic eruptions and earthquakes.

Hydrologic uses of remote sensing include the exploration for ground water in both arid and humid regions, the assessment with repetitive images of the status of perennial and intermittent lakes, the mapping of flooded areas, and the delineation of coastal and inland wetlands.

Geography is both a discipline in itself and an integration of other disciplines. Geographic uses of remote sensing data include land-use mapping in urban and rural areas, mapping of sequential changes in cultural features and their relation to the environment, and the synthesis of other resource information with geographic data to form information systems for management use.

Basic and applied research in each discipline coupled with increasing operational use of space- and aircraft-collected remote sensing data in information and resource management systems will provide a future capability for better resource and environmental management.

Geology, hydrology, and geography form a major nucleus for remote sensing activities within the United States Department of the Interior and a major role in the Department's stewardship of the public lands and resources of the United States. The Department of the Interior is custodian for the Federal Government of over 3 million square kilometers (760 million acres) in the United States and is responsible for the management of the resources and environments of those lands. It is also responsible for the management of mineral resources of almost an equal area of offshore lands on the continental shelf of the United States. To provide a sound scientific, economic, and environmental basis for its planning, policy making, and management activities, the Department continually searches for better ways to gain information about these lands and resources. Remote sensing, with its cost-effective means of data gathering, is looked upon as a new and attractive tool by the Interior Department for providing information in the fields of geology, hydrology, and departmental management. Remote sensing information is applicable not only to the public lands of the United States, but to all our lands and those of foreign countries as well. We are, of course, vitally interested in the applications of remote sensing in other disciplines such as cartography, agriculture, forestry, and oceanography. This paper, however, will be confined to the three disciplines noted above; other disciplines are discussed in other papers presented in this workshop.

Figure 1 is a map showing Federally owned lands within the United States. It is a reproduction of a page from the *National Atlas of the United States*, recently published by the U.S. Geological Survey.

GEOLOGY

The objectives of our program in remote sensing for geology and mineral and land resources are (1) to improve the observation of large geologic features

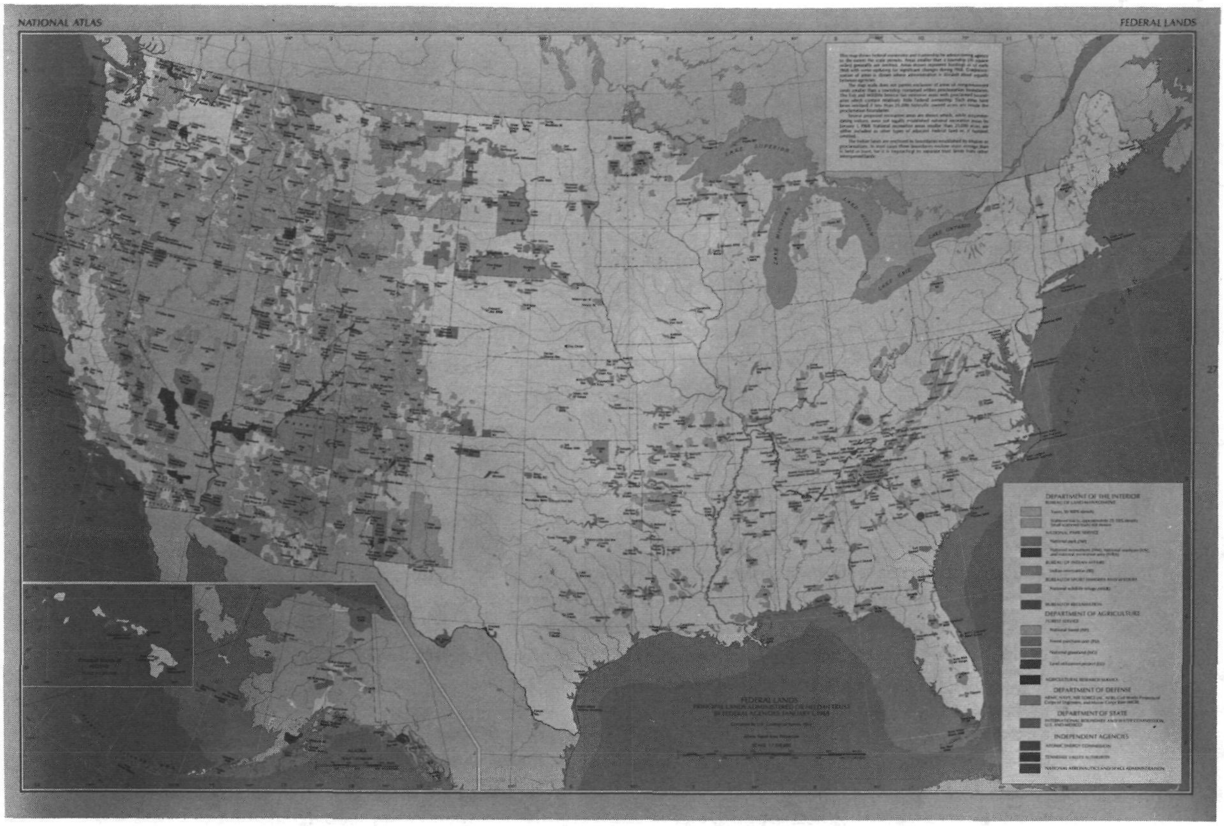

FIGURE 1. Map showing public lands managed for the U.S. Government by the Department of the Interior.

and relationships, (2) to refine structural and stratigraphic interpretations, (3) to monitor changing geologic features, and (4) to improve the efficiency of prospecting for minerals and fuels.

The use of space data for mineral resource exploration is described in this section. Normally, field aircraft observations of the terrain are synthesized into regional maps on which target areas for mineral exploration are defined. Because the bulk of such work is conducted on the ground, the field observations require a long period of time. The use of small-scale observations from space to form a regional synthesis of geologic information can be done by photointerpretive methods and promising areas can be outlined. Further details can be added by aircraft observations and later field observations. This process can significantly shorten the time required for mineral exploration and make the task much more efficient.

An example of this process shows how a mineral exploration target was detected from space photographs. Figure 2 is a space photograph of the San Carlos Indian Reservation in Arizona, taken during the flight of Apollo 9 in March 1969. The small area outlined in red is a circular feature noted on the photograph by a geologist. The photograph at lower right is an enlargement of that area, which shows that the circular feature is readily discernible on the photograph, and its presence is enhanced by the snow cover. Its identification led to the checking of an aeromagnetic map of the area, shown at left, which shows a small magnetic anomaly at the site of the circular feature. Further investigations, both by geologic mapping on the ground and by additional geophysical techniques, are being made to determine the presence or absence of a copper ore body. The presence of a significant ore body has not yet been proved, but this investigation illustrates a typical process by which exploration can proceed from space photography to ground observations. It is also worth noting that the target area is on land belonging to an Indian tribe. Thus, if the explora-

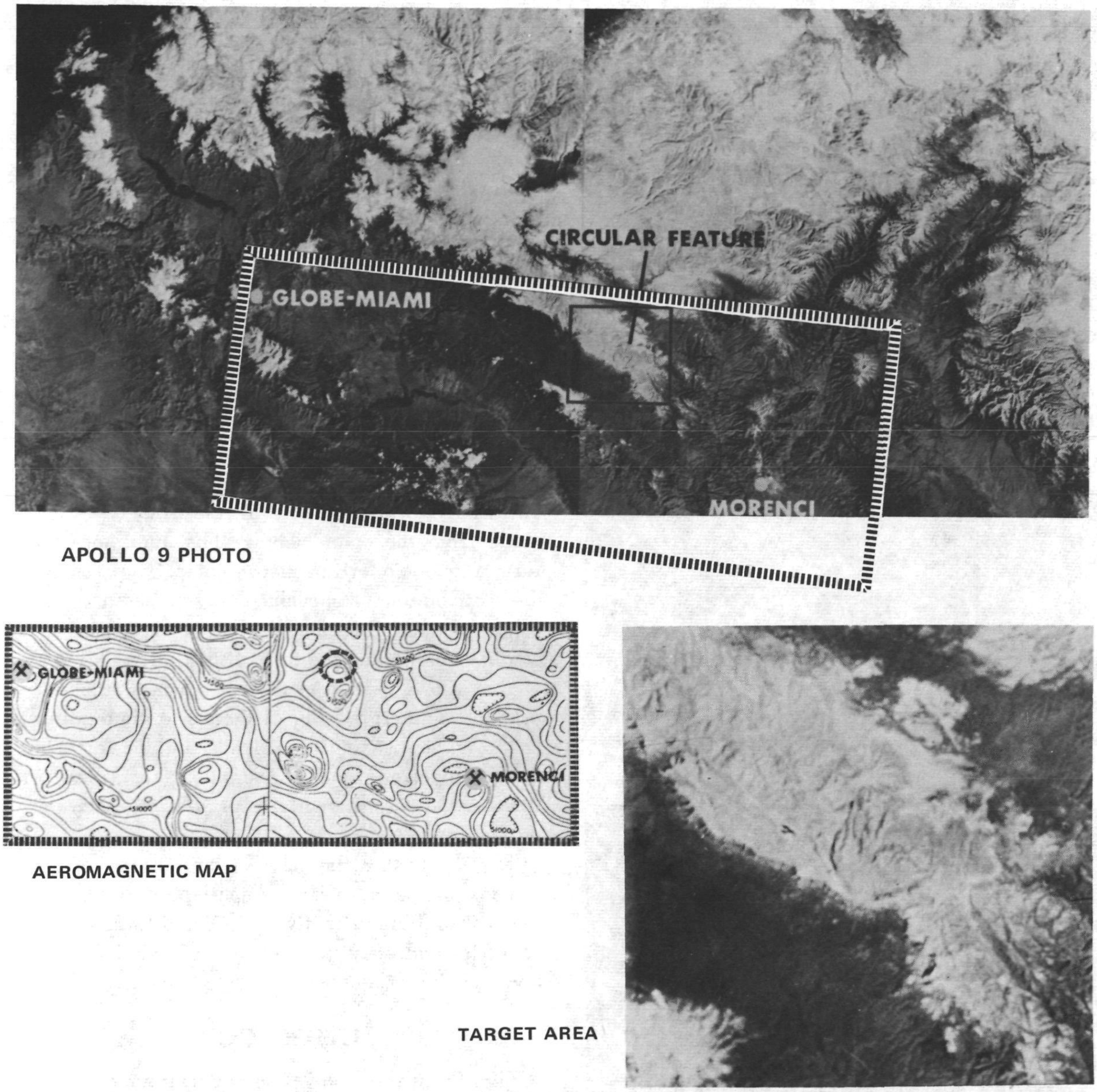

FIGURE 2. Mineral resources exploration facilitated by use of space imagery in conjunction with aeromagnetic data.

tion is successful, an increase in economic productivity can be achieved to benefit the tribe.

The ability of remote sensing to reveal hidden structures is shown by figure 3. The top photograph is a conventional black-and-white aerial photo taken from low altitude of an area in New Mexico. The presence of anticlinal structures in the area was known, but their mapping was difficult because the structures are broad and low and are not readily seen. The center view is an infrared black-and-white photograph taken in the spring. It was theorized that soil moisture, and therefore vegetation, would be less over the tops of the anticlines than over the intervening synclines and would show as a difference in tone in the photograph. This proved to be the case. The lighter-toned north-south trending areas are the anticlinal axes. The bottom photograph with the map overlay shows the location of the anti-

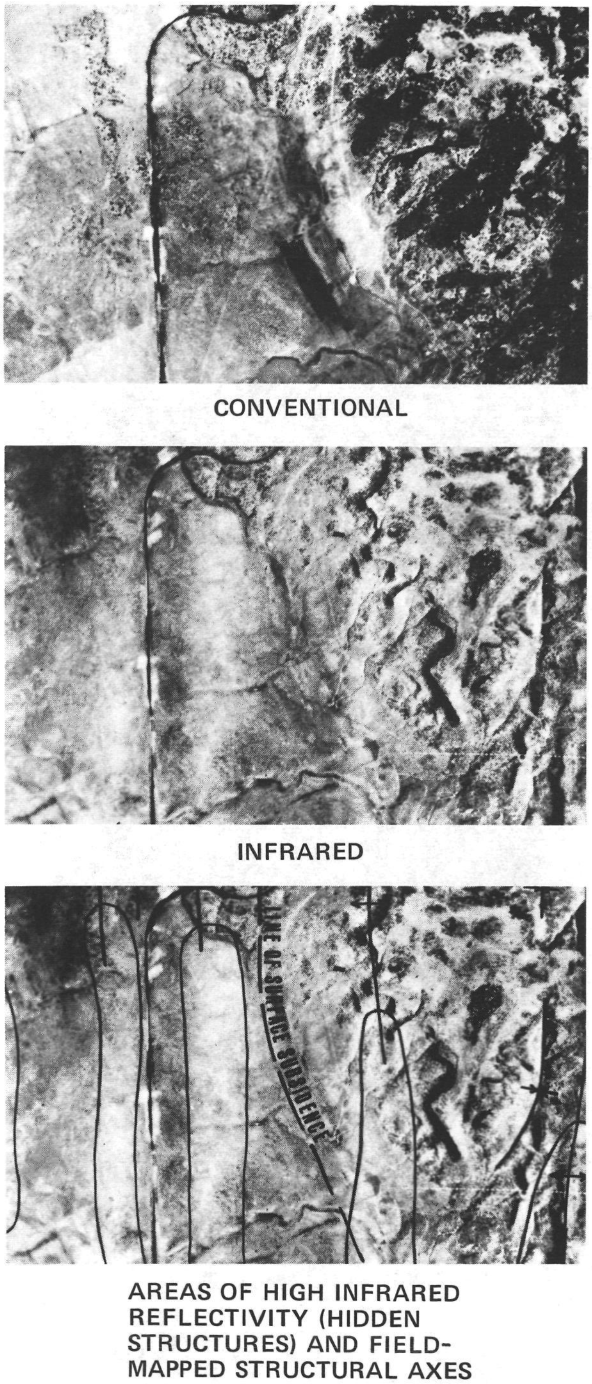

FIGURE 3. Aerial photography of the proper type and at the proper time of year has aided in the delineation of hidden anticlinical structures in New Mexico.

clines. The significance of this method lies both in the type of photograph taken and the time of year at which it was taken. Moisture and vegetation conditions at other times of the year could have been sufficiently different to mask the anticlines.

The mapping of large regions is aided significantly by space photography. Figure 4 shows a space photomosaic and two maps made by interpreting the photographs. The upper figure is a photomap of a portion of the Southwestern United States made from photographs taken on several flights of the Gemini spacecraft. A geologist who was attempting to map and correlate the soils throughout this region of the United States found the space photographs significantly more useful than aerial photographs, either in black-and-white or in color, owing to their even illumination and uniformity. Interpretation of the soil types was made from the color photographs and plotted to form a geologic terrain map (center), which shows the distribution of surficial deposits based on the colors of soils. The map is both complicated and comprehensive, and the first of its kind for a region of this size. The map at the bottom is a secondary product of interpretation of the space photographs. It shows the distribution of lands suitable for farmland, rangeland, and timberland (regardless of whether they are presently being used for such purposes).

The ability to make maps of large areas in short periods of time by means of space-photo interpretation can aid significantly in regional planning for countries and areas where such information is not now readily available.

HYDROLOGY

Significant research in the applications of remote sensing in hydrology and water resources programs has been done. Objectives were (1) to provide remote-sensing solutions to hydrologic problems, (2) to provide improved data for water management, (3) to improve forecasts of runoff from snow packs and glaciers, and (4) to measure the characteristics of water and contained substances by remote sensing.

Photointerpretation has been used extensively in exploration for ground water resources. Figure 5 shows how one space photograph taken by Apollo 9 facilitated a regional ground water appraisal. The

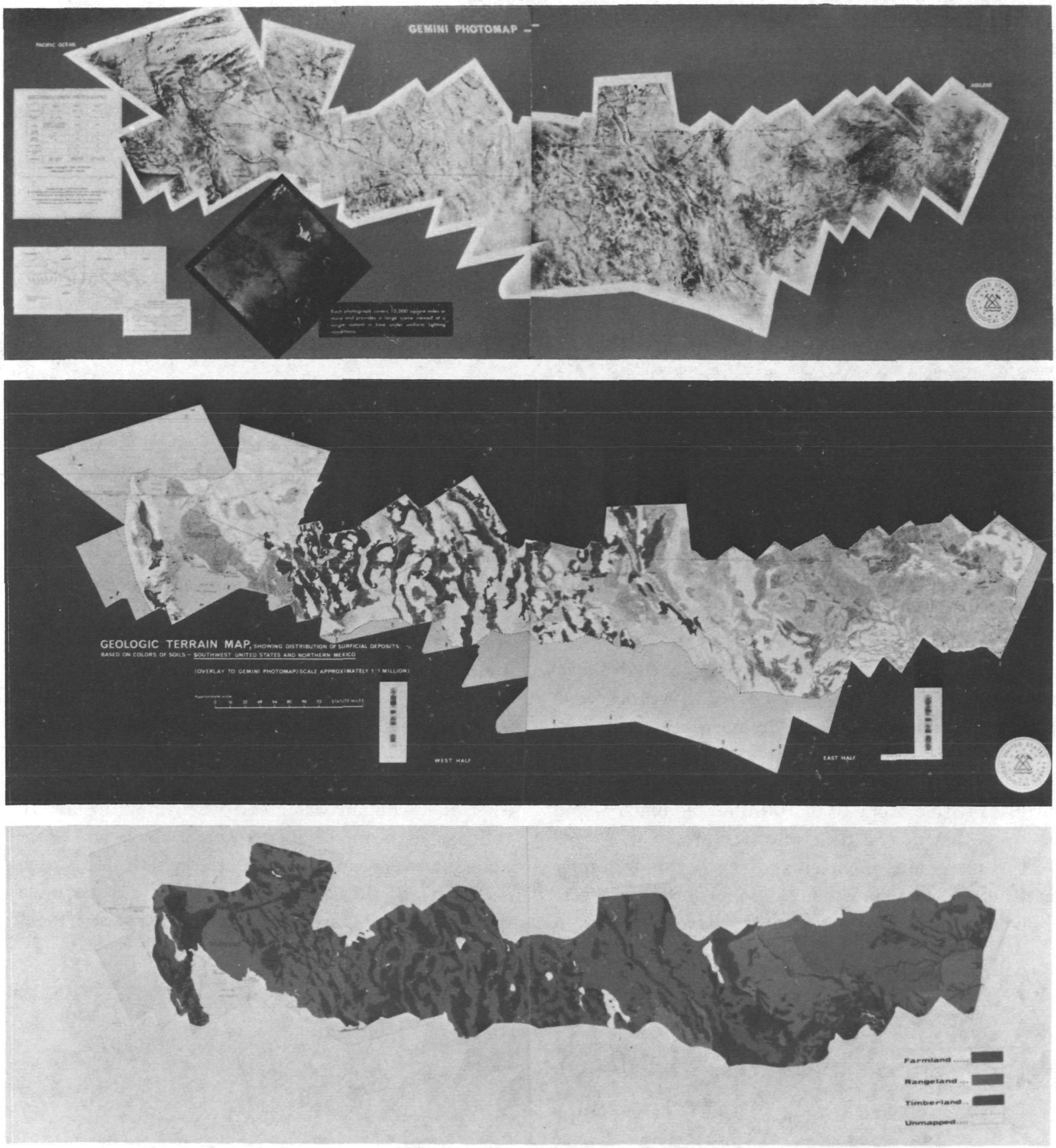

FIGURE 4. Interpretation of Gemini photographs has produced a geologic terrain map and land planning map of a portion of the southwestern United States.

area photographed is in northern Alabama, a humid region of the United States, and a portion of the folded Appalachian Mountains. The lines shown on the photograph are fracture and fault traces in the area. The solid lines indicate traces that were known previously and the dashed lines show fractures that were newly mapped from the photograph. In this region large supplies of ground water can be devel-

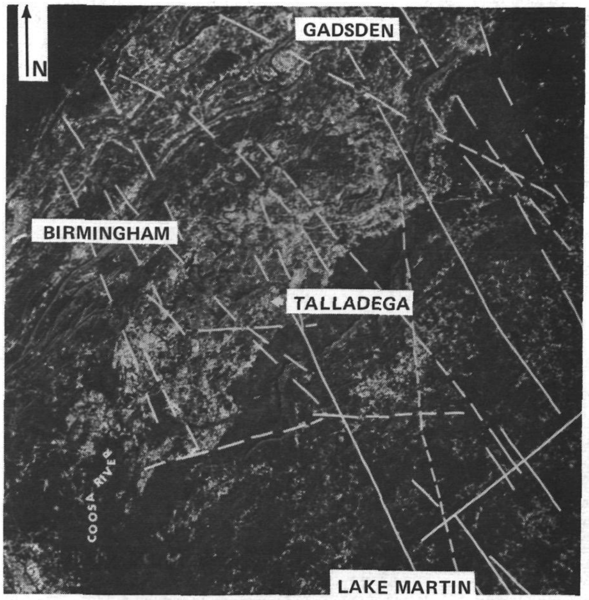

FIGURE 5. Exploration for large supplies of ground water is enhanced by mapping fracture patterns in folded rocks from an Apollo 9 photograph.

oped from wells only when they are located along fractures or at the intersections of fractures, and thus the mapping of these fractures can aid significantly in the search for new and increased ground water supplies. Wells penetrating the fractures can yield from 10 to 100 times as much water as wells that do not penetrate fractures.

The automatic processing of space photographs can aid in the delineation of some water features. Figure 6 shows how the area of surface water in a region has been mapped from an Apollo 9 color infrared photo. This is a small portion of the photograph of northern Alabama shown in figure 5. By photographic means, the area of exposed surface water was mapped for the entire photograph, as in the small portion shown on the right. Normal observations of the availability of surface water are made of the stage and discharge of streams and the stage of lakes and reservoirs. The technique of automatic mapping may provide a generalized regional index to the availability of surface water that has heretofore not been possible.

Figure 7 shows a map and an Apollo 9 photograph of an area on the edge of the arid high plains of western Texas. The geologic map shows a number of small brown dots representing playa lakes, which are intermittent storage reservoirs for water. One key to utilization of water in this arid region is the amount of water stored in these lakes that can be used for irrigation. In addition, significant amounts of ground water are mined from the thick surficial aquifer underlying the region. The Apollo 9 photograph, at lower right, shows the playa lakes. In itself, this picture provides some information as to location and area of the lakes; but, to make a complete analysis of the availability of water in this region, it will be necessary to assess the status of these lakes over long periods of time to determine when they contain water and when they do not. In addition, it is important to know which lakes lose water by evaporation to the atmosphere and which lose water by downward seepage to the water table in the aquifer. Only with repetitive space images

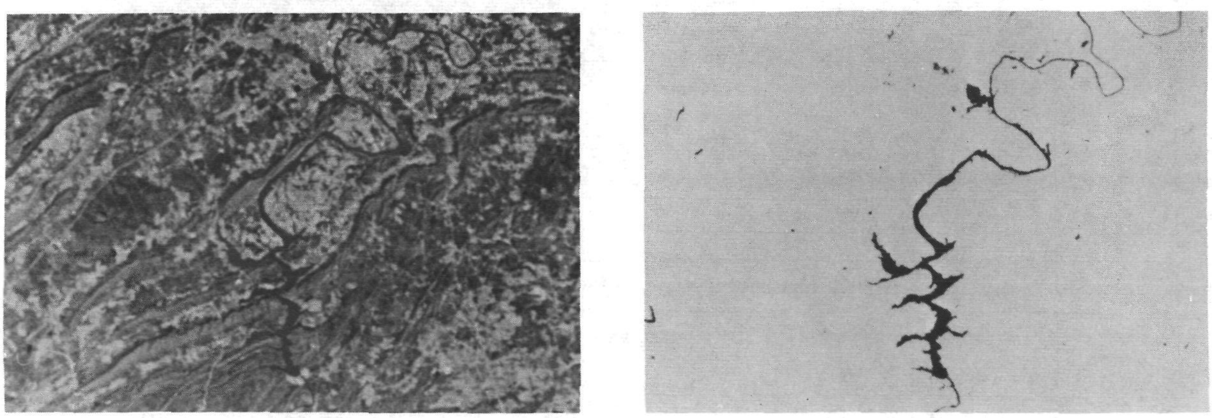

FIGURE 6. Automatic mapping of surface water can be done from space photographs by photographic means. Map at right shows water area extracted from color IR photo at left.

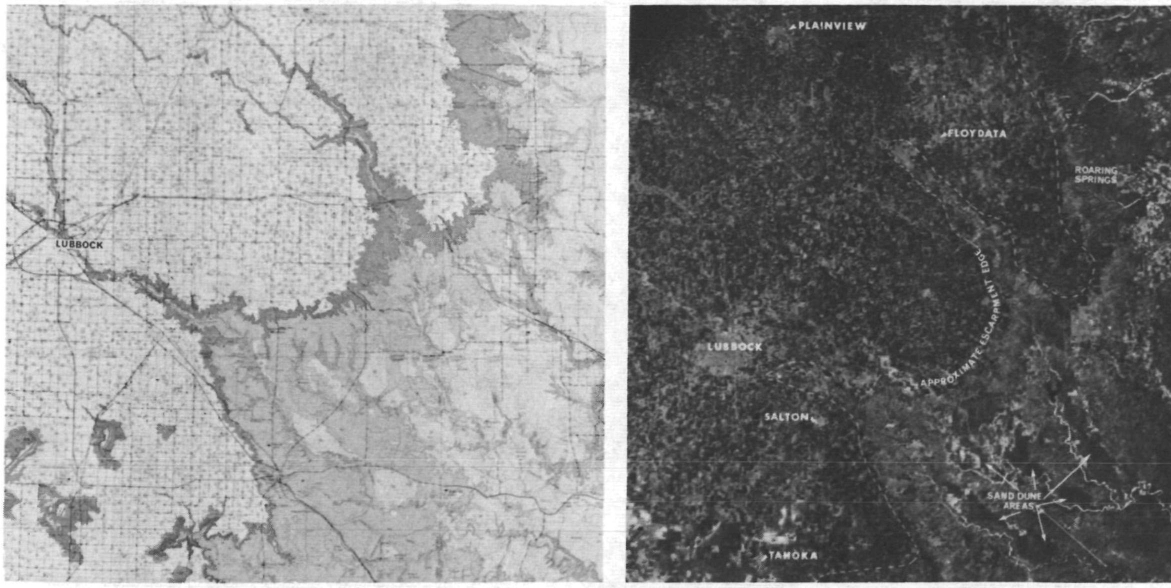

FIGURE 7. Playa lakes in the high plains of Texas can be mapped and their status assessed from space photographs.

such as those that will be obtained from ERTS-A can such an analysis be readily made. The analysis will be a key portion of water management decisions on the importation of water to the high plains from other regions to supplement the short ground water supply.

Vegetative indicators of the occurrence of ground water have long been used as guides for water exploration. Figure 8 shows land use and moisture distribution along a portion of the Texas coast. Outlined on this Apollo 9 photograph is the alluvium of the Brazos River, which flows into the Gulf of Mexico. This infrared color photograph shows differences in vegetative characteristics and moisture distribution along that coastal region, thus allowing ready identification of the permeable alluvium, which contains significantly greater amounts of ground water than the rocks on either side.

Figure 9 shows an Apollo 9 color infrared photograph of a portion of the high plains of Texas and New Mexico. This is a flat area underlain by a thick surficial aquifer. The land is primarily used for irrigated farming. The north-south line that can be seen bisecting the photograph is the State line between Texas and New Mexico. The line is visible in the photograph because of differences in land use practices and irrigation in the two States. Such a photograph shows resource managers and policy administrators the effects of land management decisions concerning the difference in allocation of water between the two States. The interpretation of such a photograph does not say, in itself, which of the two differing water allocation practices is better, but it does provide data to the managers who will make such a decision.

Figure 10 is the first space photograph of an entire flood at or near its peak. The area shown includes parts of Arkansas and Louisiana. It is difficult, time consuming, and expensive to map the extent of a large flood by ground methods, and such mapping must generally be done after the flood has receded, which means indirect methods must largely be used. The possibility of using space photographs for such a purpose is exciting to the hydrologist. It means that he may be able to obtain information on floods that has heretofore not been obtainable.

The mapping of coastal wetlands is a task of great importance not only in the United States, but in many other countries as well. Figure 11 shows two photographs taken simultaneously of the Georgia coast from the Apollo 9 spacecraft. On the left is a color infrared photograph, and on the right is a black-and-white infrared photograph. The coastal wetlands are the blue or dark-gray areas somewhat inland from the vegetated islands, which have either red or light tones. The regional delineation of such

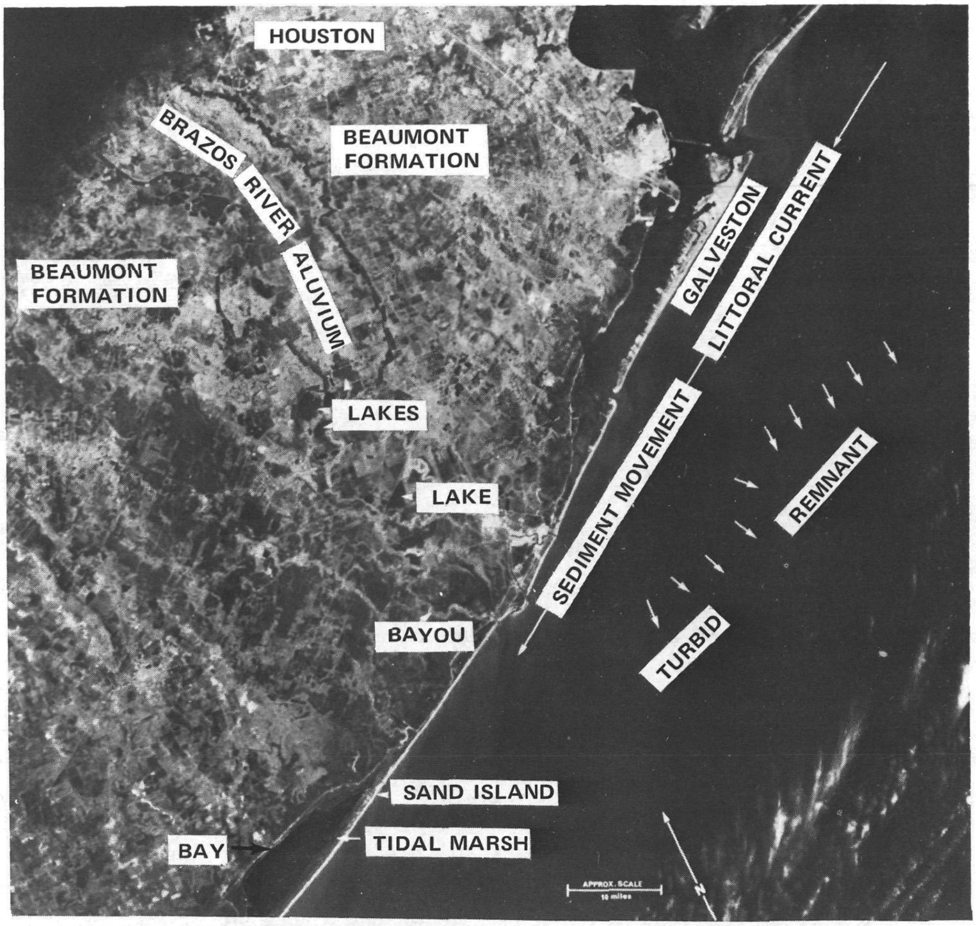

FIGURE 8. Delineation of permeable alluvium containing large supplies of ground water can be done on the basis of land use and vegetation distribution in a coastal region.

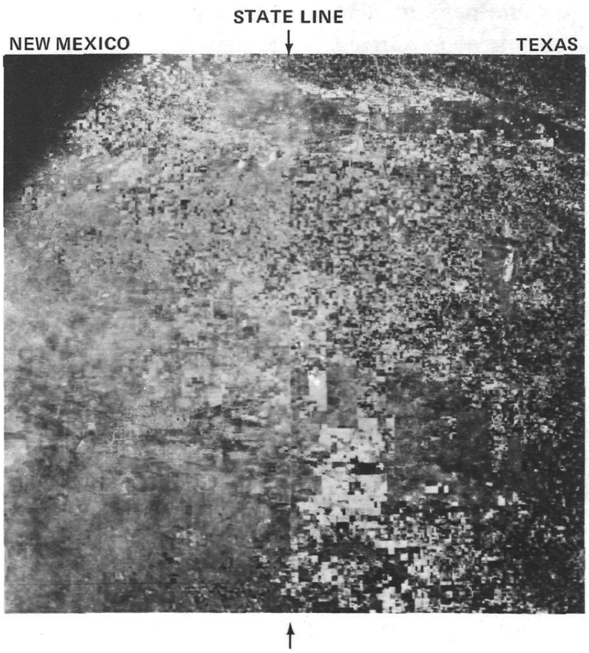

FIGURE 9. Differences in land use practices between adjacent States are shown in this space photograph.

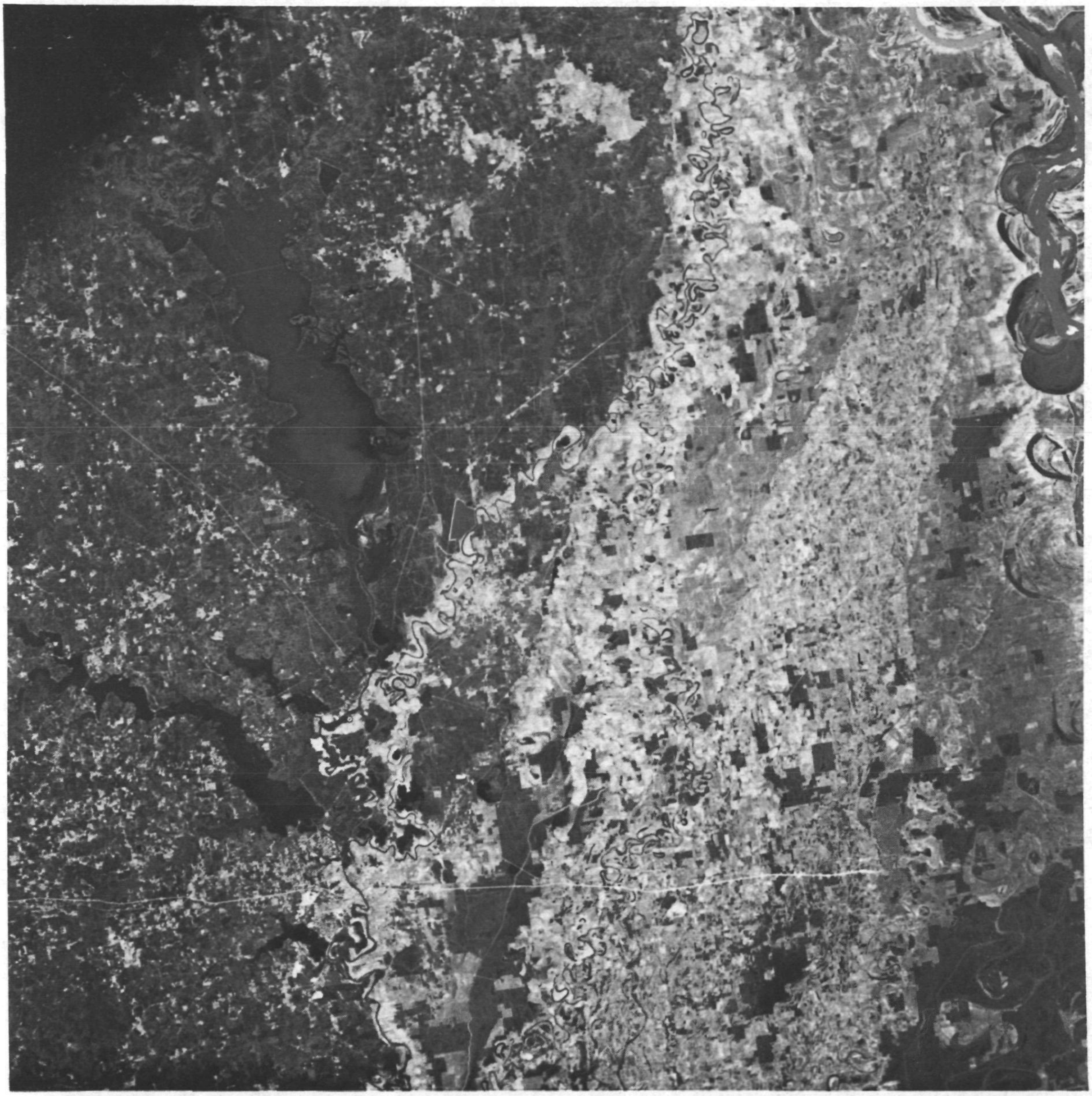

FIGURE 10. An infrared color photograph from Apollo 9 shows the extent of a flood of the Ouachita River in Arkansas.

wetlands is a simple task from this type of space photograph, which is analogous to the imagery that will be obtained from the ERTS. More detailed observations of wetlands can of course be made from low-altitude aircraft and from ground observations. The examples of remote sensing in the field of hydrology that have been shown here are primarily concerned with the mapping and identification of regional water features. Additional research has been and will continue to be conducted on quantitative measurement of water parameters, particularly those of water quality. However, such measurements generally require more sophisticated remote sensing systems than normal photographic

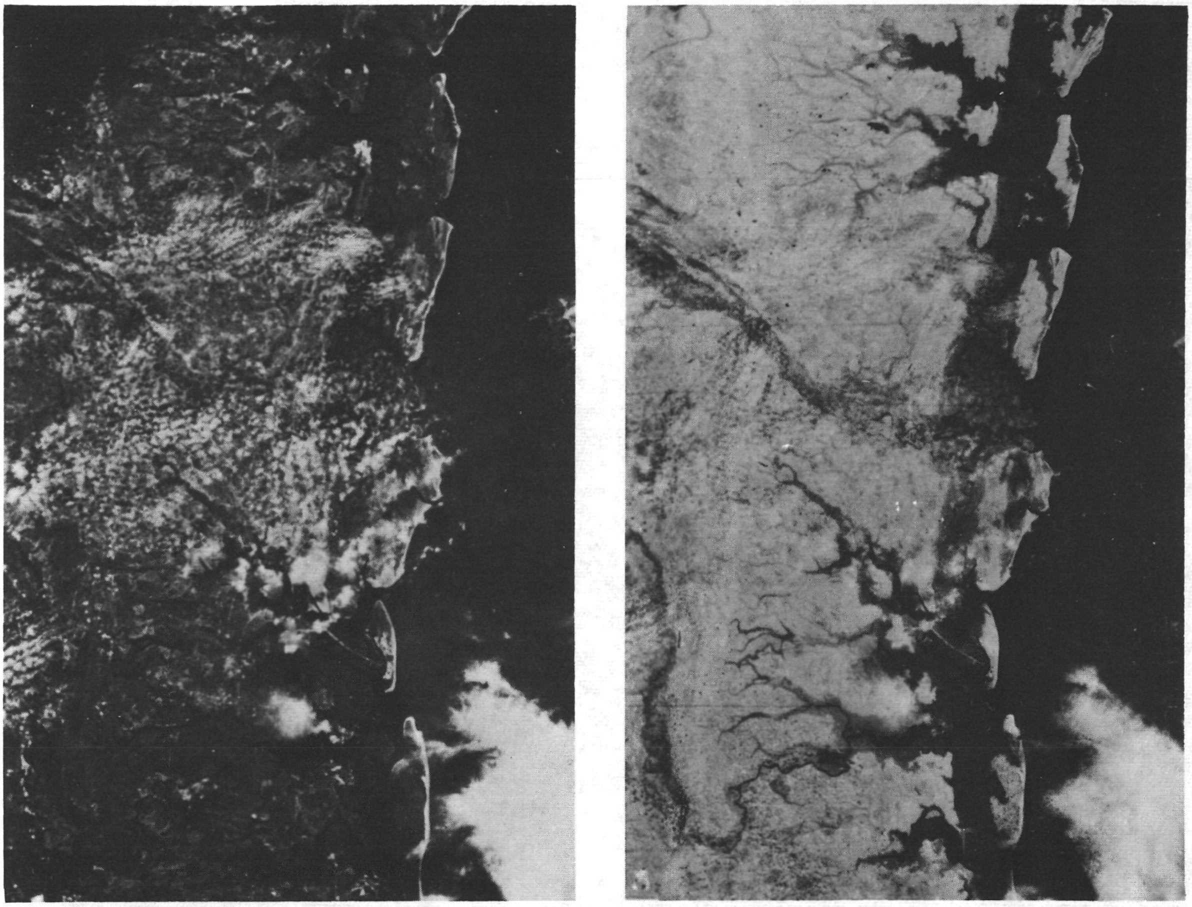

FIGURE 11. Mapping of wetlands for their management and preservation can be accomplished on a regional basis by color infrared and black-and-white infrared photography from space.

and imaging techniques and are covered in other papers presented at this workshop.

GEOGRAPHY

The discipline of geography is a major link between the resource scientist and society in general. Figure 12 shows the functions, products, goals, and clients of the geography program conducted by the U.S. Geological Survey. The goals involve the prediction of development and environmental changes which can lead to policy and management decisions for improved land use and environmental quality. To reach this goal, remote sensing data in many fields are used to map the status of lands, peoples, and environments; and to delineate the changes and rates of change of significant features. Two brief examples of such products will be given.

Figure 13 is a photograph from the Gemini 5 spacecraft of the Imperial Valley of California, an irrigated farming region. Along with this photograph is a map of land use in that region. Knowledge of the ways in which the land is used and of trends and changes in its use is of paramount importance in decisions on future development and on the consequences of present development. Methods of mapping land use from space photography are simple and straightforward and can be readily applied to information obtained from the ERTS program.

Figure 14 is an example of metropolitan land-use mapping made from an Apollo infrared photograph of the Phoenix metropolitan area in Arizona. Mapping of agricultural, urban, and other land uses is

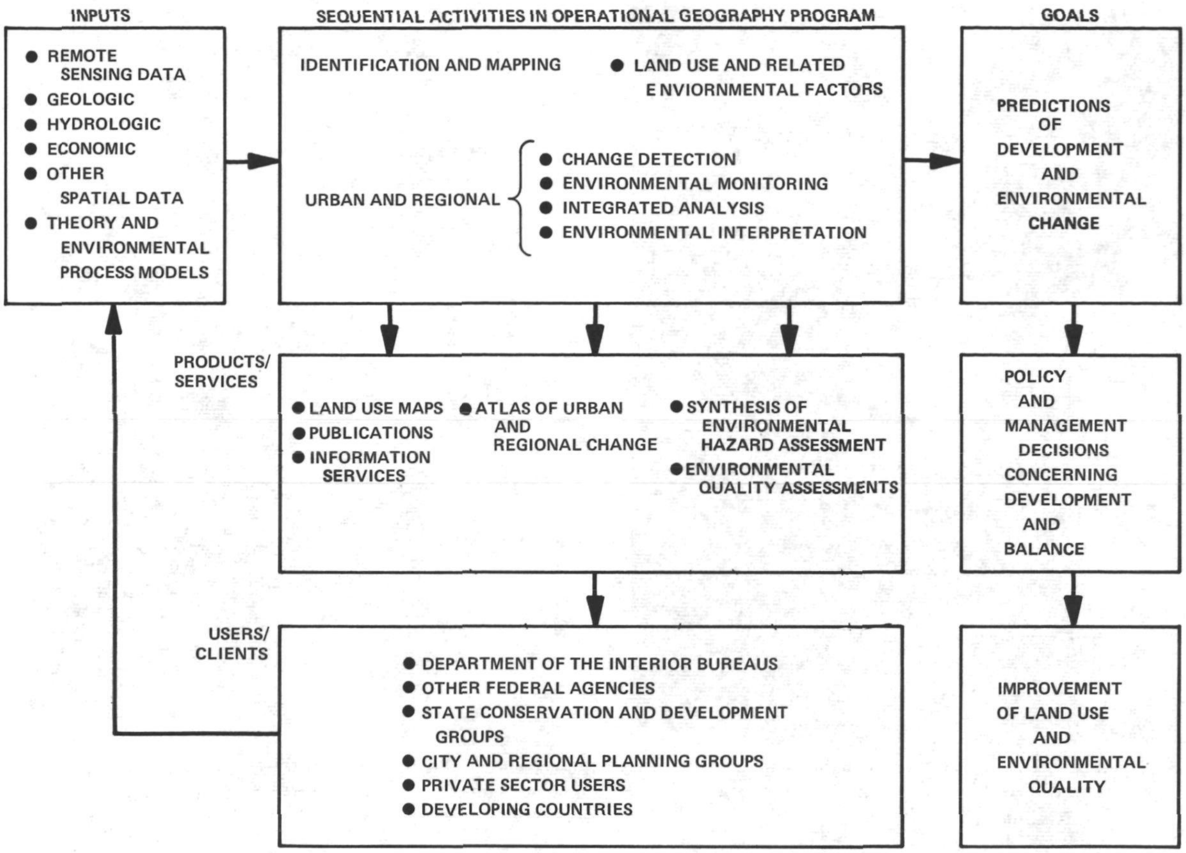

FIGURE 12. U.S. Geological Survey geography program functions, products, clients, and goals.

readily done from such a photograph. As part of the geography program, we have obtained high-altitude aerial photographs of 26 major cities within the United States during the past year. Information on land use mapped from those photographs will be correlated with census data taken in these cities in 1970 to form a data base. Images of the same areas are to be obtained by the ERTS; they will be analyzed for changes and trends in land use. An information system will be developed on the basis of such research. This system should provide usable and timely information updated at short intervals for planning purposes.

SUMMARY

In summary, basic research in applications of remote sensing to geology, hydrology, and geography has led to a determination of the feasibility of these techniques for obtaining significant information for use in management. It also provides an integration of the resource and environmental studies that historically have been conducted on separate bases. The ERTS experiment is a large-scale test of the feasibility of the data and information techniques. We will be working diligently to make this experiment a success, and we invite your participation in the program.

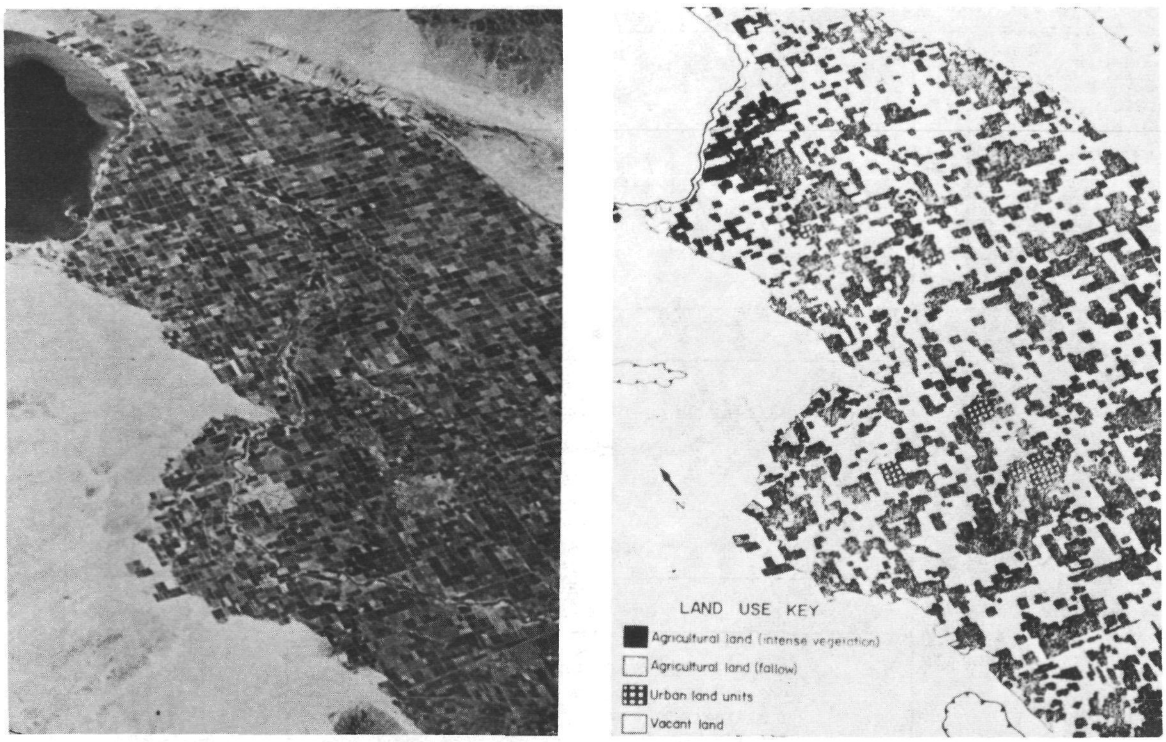

FIGURE 13. Land use can be mapped from space photographs. The map at right was made from the photo at left, which is a portion of a larger space photo of the area around Salton Sea, California.

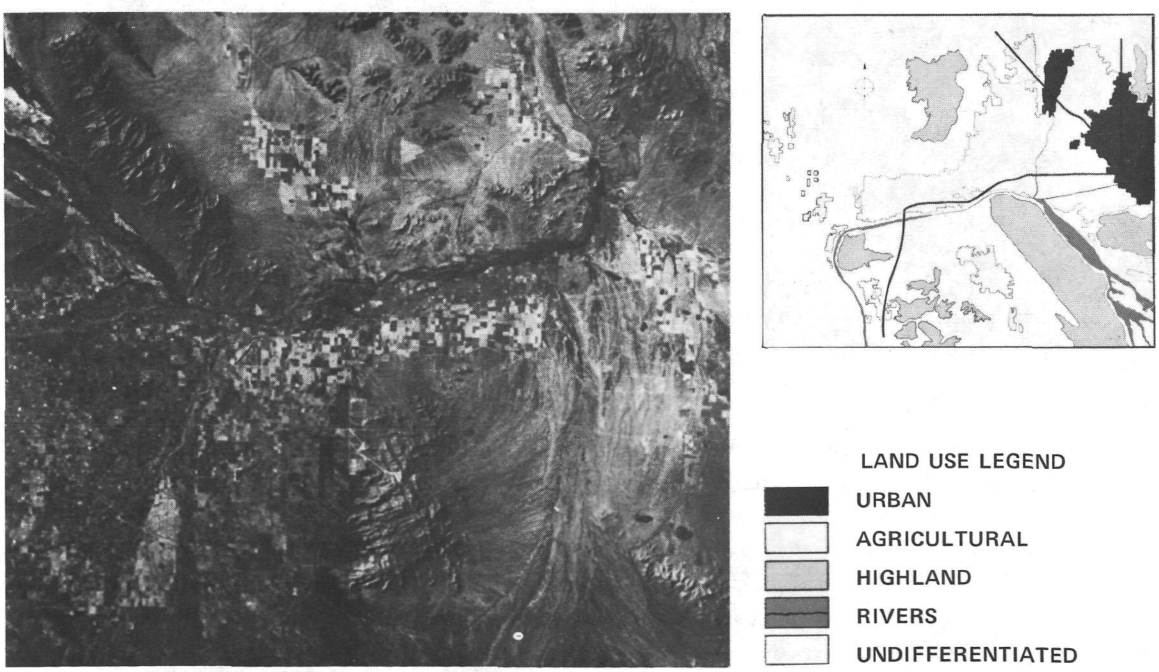

FIGURE 14. Metropolitan land use in the Phoenix, Arizona, area has been mapped from space photographs.

Applications of Remote Sensing in Agriculture and Forestry

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In January of this year President Richard Nixon transmitted to the Congress of the United States his annual Aeronautics and Space Report. Included in his letter of transmittal were several references to the potential usefulness of aircraft and spacecraft for the inventory of Earth resources. He pointed out that "the potential benefits of a viable Earth resources survey program have aroused substantial international interest" and that "we must apply space-related technology to the effective use of our resources." He further stated that "Earth resource survey satellites are planned for use, when available, to all interested countries."

Judging from the impressive roster of delegates attending this International Workshop and Symposium on Remote Sensing, there already are a great many "interested countries." Many delegates have requested that, when the first Earth Resources Technology Satellite (ERTS-A) is launched a scant 10 months from now, remote sensing data be acquired from it of Earth resources in their respective countries. It is gratifying to know that their interest in such data is not solely because of possibilities thus offered for finding previously overlooked deposits of minerals, petroleum, or other *nonrenewable* resources in their countries. Much interest is expressed also in the possibilities such data will offer for monitoring and managing various *renewable* resources, such as timber and agricultural crops, thereby placing their countries on a sustained yield basis for the production of commodities derivable from these resources.

It is primarily with this latter category of resources that my paper will deal. Furthermore, just as NASA deals with both air and space, so my paper will deal with both aircraft and spacecraft as the platforms from which remote sensing of agricultural and forestry resources can be accomplished.

RATIONALE FOR THE REMOTE SENSING OF AGRICULTURAL AND FOREST RESOURCES

Man will soon be confronted with one of the most serious crises of his existence. Basically, this crisis is developing because the world's population is rapidly increasing at the very time when many of its natural resources have dwindled to a very low level. The supply-vs.-demand problem is made even more serious by another recent development. Within the past decade a greatly increased "awareness of the have-nots," combined with an almost insatiable demand of the "affluents" for an ever-higher standard of living, has resulted in a tremendous increase in the per capita demand for earth resources at virtually every economic level in nearly every country of the world.

In view of these critical circumstances, we need the wisest possible management of the Earth's resources. An important first step leading to such management is that of obtaining resource inventories accurately and frequently.

There are two primary reasons why the inventory of timber, agricultural crops, and other natural resources can be facilitated through the use of photography taken from aircraft or spacecraft. The first of these is clearly implied in the simple statement that "the face of the land looks to the sky." The task of inventorying the Earth's resources is, first of all, one of delineating boundaries between one resource characteristic and another. When confined to Earth,

man often has great difficulty both in recognizing and in delineating these boundaries. This difficulty is attributable mainly to the limited visibility of terrain features that is afforded him, especially in areas where the topography is heavily dissected. In contrast, a "continuous plotting" of resource boundaries often can be performed on vertical photos taken from either an aircraft or an Earth-orbiting spacecraft.

The second reason for using aerial or space photography results from the sheer vastness of the areas in which Earth resource surveys must be made. It is only from aircraft or spacecraft that the broad synoptic view, so essential for the quick and economical delineation of Earth resource features, can be obtained. The fact that such vast areas can be photographed quickly and under relatively uniform lighting conditions constitutes an additional advantage resulting from the use of aircraft or spacecraft.

To better appreciate how improved resource inventories can lead to improved resource management, we need to recognize the three successive steps involved in the management of natural resources: inventory, analysis, and operation.

In the *inventory* step (the one with which most of this paper will deal), an effort is made to determine *how much* of *what* is *where* throughout the area to be managed. The *what* in this instance usually refers to such specific resources as timber, forage, agricultural crops, or other forms of vegetation and to the soil and water resources that sustain vegetation.

In the *analysis* step, certain decisions are made as to how the resources are to be managed. Such decisions are arrived at by considering two kinds of information: (1) information as to the amount and disposition of resources within the area that is to be managed, such information having been obtained in the preceding inventory step; and (2) information as to the costs likely to be incurred and the benefits likely to accrue by applying to these resources each of several management measures.

For example, will the benefit exceed the cost if we build a dam, control an infestation of weeds, or apply fertilizers to impoverished soils? Answers to such questions are in the process of changing because the world's dwindling supply of Earth resources, combined with the ever-increasing demand, is prompting even the economist to take a second look at his cost-benefit ratios. Only a few years ago forest economists in the United States usually said "We cannot afford to plant after clear-cut logging." Now they usually say "We can't afford *not* to plant."

In the *operations* step, decisions reached in the analysis step are implemented. On the one hand, these decisions are not likely to be wise unless the preceding steps (inventory and analysis) have been properly executed. On the other hand, regardless of the care with which steps 1 and 2 have been executed, nothing of consequence is done until the third step is taken. This is so because the goal is to achieve more intelligent management of the resources and thereby accomplish such specific objectives as increasing the yield of croplands and wildlands.

USER REQUIREMENTS FOR INFORMATION ON AGRICULTURAL AND FOREST RESOURCES

Primary emphasis in the present section is given to vegetation resources and information desired by agriculturists and foresters. Similar information could be given about other resources (soil, water, etc.), but to do so here would make my presentation unduly long and cumbersome.

As we begin a consideration of user requirements for information about vegetation resources, table 1 provides a useful point of departure. This table indicates that there are only four main categories of vegetation for which information is sought, viz, agricultural crops, timber stands, rangeland vegetation, and brushland vegetation. Starting with the left-hand column of the table we see that, by and large, the users of agricultural crop data need only six categories of information, viz, crop type, crop vigor, crop-damaging agents, crop yield per acre by type, crop acreage by type, and total yield. Proceeding to the other three colmuns of table 1, we note that essentially these same six categories of information are sought by managers of timber lands, rangelands, and brushlands.

Various potential users of information about vegetation resources have differing requirements as to the speed with which information must be processed, once the raw data have been collected, and also as to the frequency with which the information

Table 1. Type of information desired for vegetation resource data

For agricultural crops	For timber stands	For rangeland forage	For brushland vegetation
Crop type (species and variety)	Timber type (species composition)	Forage type (species composition)	Vegetation type (species composition)
Present crop vigor and state of maturity	Present tree and stand vigor by species and size class	Present "range readiness" (for grazing by domestic or wild animals)	Vegetation density
Prevalence of crop-damaging agents by type	Prevalence of tree-damaging agents by type	Prevalence of forage-damaging agents (weeds, rodents, diseases, etc.) by type	Other types of information desired will depend upon primary importance of the vegetation (whether for watershed protection, game habitat, aesthetics, etc.).
Prediction of time of maturity and eventual crop yield per acre by crop type and vigor class	Present volume and prediction of probable future volume per acre by species and size class in each stand	Present animal-carrying capacity and probable future capacity per acre by species and range condition class in each forage type	
Total acreage within each crop type and vigor class	Total acreage within each stand type and vigor class	Total acreage within each forage type and condition class	Same as above
Total present yield by crop type	Total present and probable future yield by species and size class	Total present and probable future animal-carrying capacity	Same as above

must be updated. This consideration has led to my compiling a second table (table 2) in an effort to document in concise tabular form the various user requirements for vegetation resource data.

Note that table 2 uses the same headings as table 1 for the four vertical columns. Table 2 also lists six time intervals that are indicative of the frequency with which various kinds of information about vegetation resources are needed.

In considering relationships between the frequency with which Earth resource data should be collected and the rapidity with which these collected data should be processed, the writer has found it useful to employ the term "half-life" in much the same way as it has been employed by radiologists and atomic physicists. The shorter the isotope's half-life, the more quickly a scientist must work with it once a supply of the isotope has been issued to him. One half-life after he has acquired the material, only half of the original amount is still useful; two half-lives after acquisition, only a quarter of the original amount is still useful, etc.

This half-life concept applies remarkably well to nearly every item listed in table 2. Specifically, if the desired frequency of acquisition of any information is divided by two, a figure is obtained indicating the time after data acquisition by which the information should be extracted from the data. It is true that some benefit will accrue even if the information does not become known until sometime

Table 2. Frequency with which information is needed for vegetation resource data (examples only)

(To convert this information to rapidity with which information is needed, see text.)

Interval	For agricultural crops	For timber stands	For rangeland forage	For brushland vegetation
10 to 20 minutes	Observe the advancing waterline in croplands during disastrous floods. Observe the start of locust flights in agricultural areas	Detect the start of forest fires during periods when there is a high fire danger rating	Detect the start of rangeland fires during periods when there is a high fire danger rating	Detect the start of brushfires during periods when there is a high fire danger rating
10 to 20 hours	Map perimeter of ongoing floods and locust flights. Monitor the Wheat Belt for outbreaks of black stem rust due to spore showers	Map perimeter of ongoing forest fires	Map perimeter of ongoing rangeland fires	Map perimeter of ongoing brushfires
10 to 20 days	Map progress of crops as an aid to crop identification using "crop calendars" and to estimating date to begin harvesting operations	Detect start of insect outbreaks in timber stands	Update information on range readiness for grazing	Update information on times of flowering and pollen production in relation to the bee industry and to hay fever problems
10 to 20 months	Facilitate annual inspection of crop rotation and of compliance with federal requirements for benefit payments	Facilitate annual inspection of firebreaks	Facilitate annual inspection of firebreaks	Facilitate inspection of firebreaks
10 to 20 years	Observe growth and mortality rates in orchards	Observe growth and mortality rates in timber stands	Observe signs of range deterioration and study the spread of noxious weeds	Observe changes in "edge effect" of brushfields that affect suitability as wildlife habitat
20 to 100 years	Observe shifting cultivation patterns	Observe plant succession trends in the forest	Observe plant succession trends on rangelands	Observe plant succession trends in brushfields

later. But the rate at which the value of the information decays is in remarkably close conformity to the half-life concept.

Each item in table 2 can be placed in one of the six categories of information listed in table 1. Thus, a certain unity can be found in these two tables. By studying them not just individually, but in concert, we can better appreciate the true nature of the multifaceted user requirement that we seek to satisfy by the remote sensing of vegetation resources.

GENERAL PROCEDURE TO BE FOLLOWED IN THE INVENTORY OF AGRICULTURAL AND FOREST RESOURCES

Specific examples given in a later section of this paper will illustrate some uses which can be made of remote sensing for the inventory of agricultural and forest resources. It should be helpful at this point to describe one such process in detail. The stepwise procedure described below pertains to the use of aerial photos, at a scale of approximately 1:20 000, for making timber volume inventories. Later examples will show how this procedure can be modified when multistage sampling with aerial and space photography is possible.

1. The total allowable expenditure of time and money for the timber volume inventory is ascertained.
2. The most suitable photography of the area, consistent with cost limitations, is procured.
3. The timber volume classes to be recognized on the photos are defined, typically, in terms of the stand-height range and crown-closure range to be embraced by each class. Some field checking usually must be done concurrently to establish "ground truth." Care must be taken at this point to be sure that enough classes are recognized to make the classification useful while avoiding the establishment of more classes than can be consistently identified on the photos, lest this lead to inaccuracies which will negate the value of the whole classification procedure. Furthermore, the classes should roughly conform to the expected range of heights and densities to be encountered in the area to be classified; otherwise, most of the plots might fall into one or two classes and nullify the primary objectives of classification.
4. From preliminary time-cost analyses, the average cost per field plot and per photo plot are determined, since it will be highly desirable to field-check several of the photo plots.
5. Also from preliminary analyses, a measure of standard deviation within photo volume classes and variance between photo volume classes is obtained.
6. From the information obtained in these preliminary steps, a determination is made of the number of ground plots and photo plots that should be taken.
7. The required photo plots are pinpointed on the photos in such a way as to achieve either a systematic or a random distribution of plots throughout the area.
8. Each photo plot is studied stereoscopically, measurements of its stand height and crown closure are made, and these figures are entered in the aerial-photo stand-volume table to compute the stand volume of the plot.
9. Distribution is made of the previously calculated number of ground plots so that the appropriate number will be obtained in each photo-volume class. In this step a sampling interval is calculated and is used to decide which photo plots in each class will also become ground plots. The interval is computed for each class by dividing the number of photo plots in that class by the number of ground plots to be taken in the class.
10. Field measurements of the timber of each ground plot are made, and from these measurements the timber volumes on the ground plot are computed. These volumes are then applied to the photo plots also, class by class.
11. The forest area within each volume class is determined, either by using a separate dot-grid count or by using the proportion of the interpreted plots occurring in each class to determine the proportion of the total area which should be allocated to that class.
12. The average timber volume per unit area per class is found and the timber-stand volume for the entire property is computed from the sums of the volumes in various classes.

Numerous modifications of the foregoing procedure can be made to adapt it to any specific timber inventory problem. In analyzing the nontimber vegetation resources of an area, basically the same procedures can be followed.

Information contained in the preceding paragraphs relative to vegetation surveys is equally applicable to soil surveys, hydrologic surveys, or surveys of most other resources of interest to the farmer or forester with respect to (a) procuring the best aerial photos consistent with budgetary limitations; (b) preliminary checking of representative areas in the field, photos in hand, in order to develop the photo-recognition features of salient types; (c) measuring distance, direction, slope, and area; (d)

determining the relative amounts of field checking and photo interpretation which should be performed during the course of the survey; and (e) compiling the final map and related statistics.

The figures which accompany this paper provide additional details on the means by which various types of Earth resources and land use categories can be inventoried with the aid of remote sensing techniques. Once the reader has examined these figures, he can better appreciate the uses and limitations of remote sensing techniques. These points are also summarized in the following two sections. To avoid making these sections unduly long and cumbersome, only photography is considered, rather than considering at each point the extent to which thermograms, radar imagery, and other forms of remote sensing data might be used. Also only vegetation and soil resources of agricultural or forested areas are considered.

IMPORTANT ADVANTAGES OF AERIAL AND SPACE PHOTOGRAPHS FOR THE EVALUATION OF AGRICULTURAL AND FOREST RESOURCES

A knowledge of the advantages which aerial and space photographs offer to the Earth resource analyst may prove of value to him in two ways: (a) It may serve to enlighten him as to a better way of doing not only the basic inventory phases of his work, but many of the associated phases as well; and (b) It may better enable him to convince a skeptical superior or other person whose cooperation is needed that such photographs offer the best solution to the resource analysis problem. In either respect, the generalized statements made in this section will assume greatest significance when viewed in the light of some specific resource-inventory project.

1. *Reliability.* The statement that "pictures don't lie" is, for all practical purposes, true of good-quality aerial and space photography. With one wink of the camera shutter, images of objects on the Earth's surface are permanently recorded in conformity with known mathematical and physical laws. Through application of these laws, the photographs lend themselves to very reliable and accurate measurement and interpretation.

2. *Favorable vantage point.* The vantage point offered by aerial and space photos is of particular importance to a mapper of Earth resources. In attempting to estimate such features as stand density, type boundaries, and general topography, the ground observer frequently is handicapped because of the restricted visibility imposed by both vegetation and terrain. Often he feels that he could assess conditions much better if only he could hover above the terrain and leisurely look down upon the entire area that is to be inventoried. Aerial and space photographs, in effect, provide him with that opportunity.

3. *Detail.* An aerial or space photograph of good quality presents almost infinite detail. It shows even more detail than could be seen with the naked eye from the same camera station, since in taking such photographs it is possible to use a lens which has much greater light-gathering power than the human eye and a photographic film-filter combination capable of penetrating haze and eliminating glare. For example, on conventional 1:20 000-scale vertical photography, taken from an altitude of 4 kilometers above the Earth's surface, small bushes and trees with crown diameters of only 1 meter are recognizable individually, and narrow linear objects such as trails, pipelines, and even fences are frequently identifiable. On space photographs obtained by the Apollo and Gemini vehicles, resolution often has been poorer than this by two orders of magnitude. The combination of such aerial and space photographs, however, when used in a multistage sampling scheme, can provide a very powerful set of inventory tools.

4. *Completeness of coverage.* The photo interpreter can study vegetation and soil conditions in 100 percent of the area with which he is concerned. The ground survey crew, by contrast, can rarely make a detailed study of more than 5 to 10 percent of the area and must assume this sample to be representative of the entire area. The photo interpreter usually can see such features as roads, streams, ridgelines, vegetation-type boundaries, and sometimes even soil-type boundaries throughout their entire extent and can therefore employ "continuous plotting" methods when mapping them. The ground mapper often must interpolate the portions of these features which he never sees while running widely spaced strips through the area.

5. *Depth perception.* If two aerial photographs of

an area taken from different camera stations are properly viewed simultaneously, a three-dimensional image is obtained which greatly facilitates photographic interpretation. Under favorable conditions, and with the aid of rather inexpensive photogrammetric instruments, the trained photogrammetrist can measure heights of trees and differences in ground relief with an average error of less than 6 meters on 1:20 000-scale aerial photos, and he can delineate contours with sufficient accuracy for many resource planning purposes. However, as might be expected, depth perception on space photographs often is at least one order of magnitude poorer than on such aerial photographs.

6. *Ease of interpretation.* The shape, tone, texture and relative size of objects appear much the same on a photograph as they would to the naked eye if viewed from the camera station. It therefore is frequently easier to interpret a photograph than even the most carefully prepared map, because the latter must resort to the use of symbols. The three-dimensional nature of the photographic image further facilitates its interpretation.

7. *Opportunity to extend limited ground observations.* Such features as species and soil types sometimes cannot be interpreted directly from aerial or space photographs. However, ground observations made with field binoculars from favorable vantage points can give such information for various spots identifiable on the photos. Then, by photographic interpretation, the areas in which determinations have been made can be compared with other areas having a similar photographic appearance. Type boundaries can then be delineated on the photographs and transferred to a type map. Furthermore, this can be done without the ground observer's having to keep track at all times of his bearing and distance from some reference point. By such use of aerial and space photos to extend limited ground observations, the amount of field work required on a variety of resource evaluation problems can be appreciably reduced.

8. *Ease of measurement.* Many measurements of distance, direction, and height which, prior to the advent of aerial and space photography, could be made only in the field by the resource mapper, now are made with comparable or even superior accuracy directly on the photographs. In making measurements in the field, crews may be hampered by poor visibility, fatigue, adverse weather conditions, and the pressure of trying to complete a given set of field measurements in time to return to base before nightfall. None of these adversities need hamper the photogrammetrist who, by working under the more favorable and uniform conditions of his office, is capable of making unhurried measurements with a consistently high order of accuracy.

9. *Ease of checking for sources of error.* If a field traverse (of the type sometimes required in making Earth resource surveys) fails to close, it may be necessary to repeat the entire traverse in order to detect the source of error. However, if a photogrammetric traverse fails to close, the source of error usually is readily found. Similarly, the field supervisor who attempts to check the work of several field crews may find that a large part of his time is spent merely in traveling from one crew to another. The photogrammetric or photo interpretation supervisor ordinarily does not encounter this difficulty because the modest office space requirements of his staff make for compactness of the unit.

10. *Opportunity for study of the area during the entire year.* In many of the less developed areas, inclement weather hampers or prevents the performance of important field activities, including topographic mapping and timber cruising (i.e., timber volume estimation). Those who are expert in the performance of these types of field work can therefore be hired only seasonally, unless it is possible for the employer to tide them over with other forms of work, at which they usually are less proficient. The use of aerial and space photographs by resource mappers appreciably decreases the amount of field work required. By proper planning it usually is possible to have the crews complete field work during periods of favorable weather and to perform, in the office, some photogrammetric and photo interpretation phases of the same project during slack periods caused by inclement weather. This results in greater continuity of employment and in performance by the same individual of both the field and office phases of vegetation-soil evaluation projects in which photos are used. Such an arrangement is highly desirable since it gives the photo user an opportunity to make frequent field checks as to the accuracy of his interpretations. The opportunity for study of aerial and space photographs during the entire year is of further advantage

to those who may wish to know immediately what the Earth resource conditions are in a given area which at the moment is not accessible for ground study.

11. *Rapidity of obtaining inventory data.* In many of the less developed parts of the world, areas in which vegetation and soil resources are to be evaluated are vast, extremely difficult to reach, and, once reached, must be laboriously studied. Since the obtaining of inventory data is the first step in the development of the resources inventoried, it is very desirable to have a rapid means of obtaining this information so that resource development on a large scale can be undertaken promptly. The efficient use of aerial and space photos, combined with only a limited amount of field work, provides such a means.

12. *Suitability for comparative studies.* Often the vegetation expert or soil scientist who is making studies in plant succession, soil erosion, growth, and related phenomena has need for detailed information regarding conditions as they existed in the area at various periods of time prior to the present study. Aerial or space photography obtained periodically of the area being studied constitutes an irrefutable means of dating events and situations in the area of interest.

13. *Suitability for filing.* Because of their convenient and uniform dimensions, compactness, permanency, and systematic numbering, aerial and space photographs are ideally suited to filing. They are so placed in a vertical file cabinet that the title and number designation of each print appear at the top where they are easily read when leafing through a folder of photographs. When it is desired to view the photographic prints of a given area, the numbers of the prints covering that area are readily determined by reference to a photo index. The desired prints can then be located in the file cabinets in a matter of a few seconds. Because of their compactness, approximately 6000 prints can be filed in a single vertical file cabinet of standard size. At a scale of 1:20 000 with conventional amounts of overlap, these prints would cover nearly 40 000 square kilometers. (By contrast, one typical space photograph covers an area of 26 000 km^2.)

14. *Economy.* The savings which can be effected through the intelligent use of aerial and space photographs in making resource evaluations, while known to be great, are very difficult to estimate. There may be not only a reduction in the cost of doing a given job through the use of such photographs, but also an appreciable increase in the accuracy obtained and a decrease in the time required to obtain sufficient information to commence development of resources. The indirect savings, consequently, may be even greater than the direct ones. In the United States, the cost of having 1:20 000-scale aerial photos taken varies from less than $2 to more than $12 per square kilometer, depending upon such factors as size and shape of the area to be photographed, proximity to an airfield, and frequency of days suitable for the taking of photographs. The cost of purchasing overlapping prints from existing photography of the same scale is about 12 cents per square kilometer. These photographs, once procured, can be used in a variety of ways, including the preparation of several kinds of maps (planimetric, topographic, vegetation type, soil type, etc.), the preliminary location of transportation routes, and the preliminary location of sites wherein the soils and climatic factors are favorable for the production of certain kinds of crops. Until it is known how many of these uses will be made of the photographs, it is difficult to know how to prorate the cost of procuring them and making base maps from them on which to plot resource inventory data. In general, however, the larger and less accessible the area in which a resource inventory is to be made, the greater the savings effected, per unit area, through use of aerial photographs. The use of a typical unmanned space vehicle in the near future will entail an estimated cost of 3 to 5 million dollars. However, if placed in polar orbit, it can photograph the entire globe several times, weather permitting. When the total cost is prorated over so vast a land area, the cost per unit area is even less than that of conventional aerial photography. At present, of course, it is not realistic to assume that a substantial use would be made of such photography for *all* of the land area photographed.

IMPORTANT LIMITATIONS OF AERIAL AND SPACE PHOTOGRAPHS FOR THE EVALUATION OF AGRICULTURAL AND FOREST RESOURCES

A knowledge of the limitations which aerial and space photographs impose on the Earth resource analyst should prevent him from making serious

errors in estimating the speed and accuracy with which he will be able to evaluate Earth resources. The following are among the more important of these limitations.

1. *Aerial and space photographs do not entirely eliminate field work.* For example, the determination of such important items as timber-species composition, current rate of growth, merchantable length of stem, taper of stem, and amount of defect usually must be made with the aid of frequent on-the-ground checks. Likewise, if accurate base maps are to be constructed photogrammetrically on which the Earth resource information can be plotted, work on the ground is required in establishing the basic network of horizontal and vertical control points, the names of certain features, and the location of property boundaries. Field work also may be necessary to determine the exact course followed by secondary roads and trails which wind beneath a dense canopy of tree crowns. The configuration of contours or the nature of understory vegetation in areas defiladed from the camera station by intervening foliage or obscured by dense shadows likewise can be determined only through the making of numerous field observations.

2. *Prolonged training and careful supervision of photogrammetric and photo interpretation personnel may be required.* A student can be taught to do reliable timber cruising or soil and vegetation type mapping by strictly ground methods in a relatively short time. If he is to learn methods involving the use of aerial or space photographs, prolonged training may be required. For example, a training period of 6 weeks or more may be required to teach the student how to do reliable timber-stand classification from aerial photographs. Furthermore, frequent expert supervision of his photographic interpretation coupled with periodic field checks is necessary to ensure that he does not gradually and erroneously revise his impression as to the photographic characteristics of the various timber-stand classes. Even a matter as straightforward as the estimation of tree heights by measurement of photographic parallax may require upwards of 100 hours of training before the student has mastered the "feel" of making correct photo measurements. He obviously can be taught ground methods of reliably measuring tree heights in a much shorter period.

3. *Scale usually varies throughout a photograph.* A map of a small area, being an orthographic projection of a portion of the Earth's surface, shows all objects at constant scale and in the same plan-relation to each other that they bear on the ground. Therefore true directions, distances, and areas can be determined directly from a map. An aerial photograph, being a perspective projection of a portion of the Earth's surface, is subject to relief displacements. (Such displacements usually are negligible on space photographs.) In addition, both aerial and space photographs usually contain tilt displacements. For these reasons they do not show all objects in their true relative positions at constant scale. Accordingly distances, directions, and areas as estimated directly from measurements made on such photographs may be very seriously in error unless the photos are suitably rectified. This process is performed routinely and at low cost in many large photogrammetric projects, however.

4. *Photographs may emphasize the wrong features.* Objects which are in direct sunlight and in direct view from the camera station tend to appear the most conspicuous on aerial and space photographs regardless of their importance to the resource analyst. For example, aerial photography of a forested area often reveals a wealth of relatively unimportant tree-crown detail at the expense of showing clearly such important features as roads, trails, streams, understory vegetation, rock outcrop beneath the trees and, indeed, the soil itself. To those charged with evaluating and developing the resources of an area, the importance of the latter features usually is greatest in areas having the highest merchantable timber volume, whereas the opportunity to discern them on aerial photographs usually is poorest in such areas.

5. *Photographs may rapidly become outdated.* A wildland or agricultural area is not a static community, but one which is constantly changing. Current aerial and space photography may be very useful for making vegetation and soil inventories, insect and disease appraisals, soil erosion analyses, snow surveys, and related studies. However, photography taken at an earlier date may be worse than useless for such studies if it leads to fallacious conclusions as to the present nature of the area, derived from obsolete photographic data.

6. *A single photograph rarely shows all of the*

desired area. Boundaries of the area shown on a single aerial photograph usually bear no relation to boundaries of the area of interest to a soil scientist or vegetation analyst. Commonly the photo shows only part of the desired area and also shows parts of surrounding areas with which these men are not concerned. They therefore may find it necessary to "piece together" a number of photos in order to get an overall picture of the area of interest. In contrast, a map can be made of such dimensions as to show the entire area at a common scale on a single sheet. While the foregoing constitutes a very real limitation to the direct use of aerial photographs, it is to be emphasized that the map which overcomes this difficulty, as well as some of the difficulties previously mentioned, often can best be made from the aerial photographs. In addition, it must be realized that a typical space photograph often presents no problem whatever in this regard.

SOME SPECIFIC EXAMPLES OF THE USE OF REMOTE SENSING IN AGRICULTURE AND FORESTRY

Determining the Vigor of Vegetation

As indicated in table 1, all managers of vegetation resources are interested in monitoring the vigor of plants which they seek to manage. At present, the best possibility for determining the vigor of vegetation is usually offered through photographically recording foliage reflectance in the near infrared (figure 1). The reason has not yet been fully ascertained, but the most probable explanation is as follows.

The spongy mesophyll tissue of a healthy leaf, which is turgid, distended by water, and full of air spaces, it a very efficient reflector of any radiant energy and therefore of the near infrared wavelengths. These wavelengths pass through the intervening palisade parenchyma tissue (which absorbs blue and red and reflects green from the visible). When its water relations are disturbed and the plant starts to lose vigor, the mesophyll collapses, and as a result there may be great loss in the reflectance of near infrared energy from the leaves almost immediately after the damaging agent has struck a plant. Furthermore, this change may occur long before there is any detectable change in reflectance from the visible part of the spectrum, since

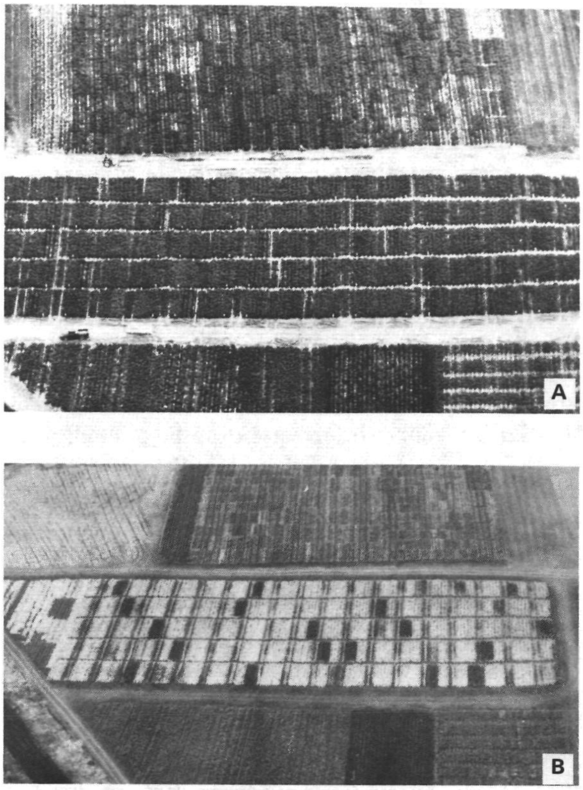

FIGURE 1. Late blight of potato is more easily discerned on infrared film (B) than on panchromatic film (A). (Courtesy Manzer and Cooper, University of Maine.)

no change has yet occurred in the quantity or quality of chlorophyll in the palisade parenchyma cells.

To detect this change photographically, a film sensitive to these near infrared wavelengths is used. Black-and-white infrared-sensitive films are sensitive not only to the near infrared but also to much of the visible spectrum. To obtain maximum tone contrast between healthy and unhealthy foliage at this early date in the development of the disease, we should use only the near infrared region, where changes in reflectance have occurred. Consequently, a deep red filter (Wratten 89B) is commonly used in conjunction with the infrared-sensitive film, since this filter effectively prevents the unwanted wavelengths from reaching the film. On positive prints made with this infrared-89B combination, healthy plants consistently appear lighter in tone than unhealthy ones. Panchromatic or conventional color photography (e.g., aerial Ektachrome) taken at the

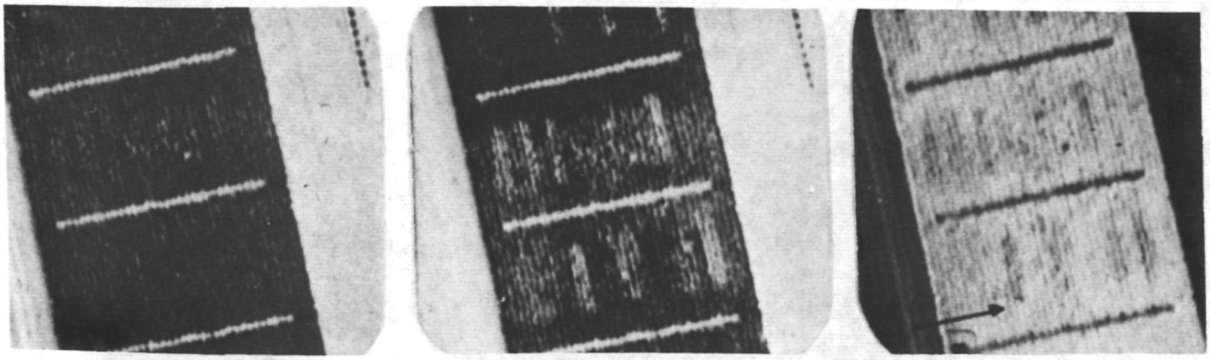

FIGURE 2. These three simultaneous photos illustrate the value of multiband photography for the identification and analysis of "mosaic disease" on sugar beets grown in an experimental plot on the Davis Campus of the University of California. Diseased areas are of the same tone as bare soil in the middle and right photos; hence, the left photo is needed to show which parts of the field are devoid of vegetation. The most recently infested areas appear dark in tone on the infrared photo (arrow) before they appear light in tone on the middle photo, which was taken with panchromatic film and a light, haze-cutting filter, thus recording only the visible portion of the spectrum. Hence the middle and right photos are needed to differentiate recent from older disease infestations and thereby measure rate and direction of spread. The three-band "tone signatures" summarized below are thus seen to be necessary and sufficient for differentiating the four resource categories of interest in this area:

Type of resource feature	Tone as a function of spectral band		
	Ultraviolet	Visible	Infrared
Bare ground	Light	Light	Dark
Healthy vegetation	Dark	Dark	Light
Recently diseased vegetation	Dark	Dark	Dark
Previously diseased vegetation	Dark	Light	Dark

same time, however, shows little or no tone difference between the healthy and the unhealthy plants, regardless of the filter used. (As the term panchromatic implies, this film is sensitive to all colors of the visible spectrum.) Corollary to the fact that at this early date we cannot obtain a tone difference between healthy and diseased plants on panchromatic or aerial Ektachrome film, neither can we see a color difference with the naked eye. This leads to the rather startling conclusion, already borne out by numerous tests, that a loss of vigor in many plants can be seen more readily on infrared photography taken from an altitude of several kilometers above the Earth's surface than by an expert on the ground as he walks through the fields.

Eventually the loss of vigor may also lead to a reduction in the chlorophyll content of leaves and to an unmasking of the yellow pigments. By that time the unhealthy plants exhibit a characteristic yellowish appearance, in contrast with the normal green plants; and this difference in spectral reflectance can be discerned on panchromatic photography taken with either a minus blue (Wratten 12) or a light red (Wratten 25A) filter. (See figures 2 and 3.)

False color films that have infrared sensitivity also can be used in the early detection of loss of vigor in plants. The purpose of the false color is to accentuate certain features and facilitate the making of certain distinctions, even at the expense of making features of lesser importance less interpretable. One such film is Kodak Infrared Aero film (E-3 process) which also is referred to either as infrared Ektachrome or color infrared film. Since the film is normally exposed through a Wratten 12 filter, blue light does not contribute to formation of the image. The three dyes of this film respond to green, red, and infrared wavelengths, respectively, with the net result that green objects (except healthy vegeta-

FIGURE 3. Panchromatic vertical aerial photograph of orchards in the Santa Clara Valley of California in which the light-toned circular spots indicate areas where the stone fruit trees (mainly prunes and apricots) are suffering from attacks by the oak root fungus (*Armillaria mellea*).

tion, which is also highly infrared reflective) appear blue, red objects appear green, and infrared-reflective objects which have relatively low reflectance in the visible part of the spectrum (such as healthy vegetation) appear red.

Because of the unusual colors with which features are rendered on infrared Ektachrome film, we would do well to describe the unique properties of this film. This is doubly important because image color is used to such an extent in identifying vegetation types and estimating plant vigor on this type of photography. Consequently, unless the photo interpreter knows the spectral responses of the three-layer emulsion comprising that film, he is likely to make many erroneous interpretations of photography taken with it.

Infrared Ektachrome is known as a "subtractive reversal" color film. In such a film, dye responses (when the film is processed) are inversely proportional to the exposures received by the respective emulsion layers. In devising infrared Ektachrome film, the manufacturers had one major objective in mind: that of causing healthy vegetation to exhibit a strong photographic color contrast with respect to all other features. More specifically, it was decided that a substractive reversal photographic film should be devised on which healthy vegetation would appear bright red while everything else would appear in colors other than red. To accomplish this objective, it was necessary to exploit the fact that healthy vegetation exhibits very high infrared reflectance and relatively low reflectance of visible light. Thus, when the manufacturers were devising the three-layer emulsion of infrared Ektachrome film, they linked a cyan dye to the infrared-sensitive layer of the film, and they linked yellow and magenta dyes to the green- and red-sensitive layers, respectively. Although this film has undergone some modifications since it was first produced during World War II as "camouflage detection film," the foregoing is an accurate description of its present characteristics. Whatever blue-sensitivity exists in the three layers is rendered inconsequential through use of a "minus blue" (Wratten 12 or 15) filter over the camera lens at the time of photography.

Consistent with the foregoing, and keeping in mind that dye responses are inversely proportional to exposures received, the following responses occur in each area on infrared Ektachrome film where healthy vegetation is imaged: (1) There is a great deal of yellow and magenta dye left in the film after processing, because the film was only weakly exposed to the red and green wavelengths to which those dyes, respectively, are linked; and (2) there is little or no cyan dye left in the film after processing because the film was strongly exposed by infrared wavelengths to which that dye is linked.

When processed infrared Ektachrome film in transparency form is viewed over a light table through which white light is shining (i.e., light which contains approximately equal amounts of blue, green, and red), the following factors are operative in those parts of the transparency where healthy vegetation is imaged: (1) The concentra-

tion of yellow dye is so high that blue light is almost completely absorbed, (2) the concentration of cyan dye is so high that green light is almost completely absorbed, and (3) healthy vegetation appears red. Since virtually no other features have this peculiar combination of spectral reflectances, there are no other features which appear red on the transparency. Because of its sensitivity to long wavelengths and the exclusion of short ones through use of a Wratten 12 filter, this film has the ability to penetrate haze exceptionally well.

A false color film containing only two dyes and known as "SN-2 spectrozonal film" is produced in the U.S.S.R. One layer of the emulsion responds to visible wavelengths of energy; the other, to infrared wavelengths in the 0.7-to-0.9-μm region. During film development, color dyes are introduced into both layers to produce images in various colors.

Figure 4 shows several representative examples of the appearance of healthy and unhealthy vegetation on infrared Ektachrome photography. The blue-green color of unhealthy foliage (such as that to the left of the number 6 on figure 4) is in sharp contrast to the bright red of healthy foliage (such as that to the left of the number 7).

A few studies have indicated that loss of vigor in

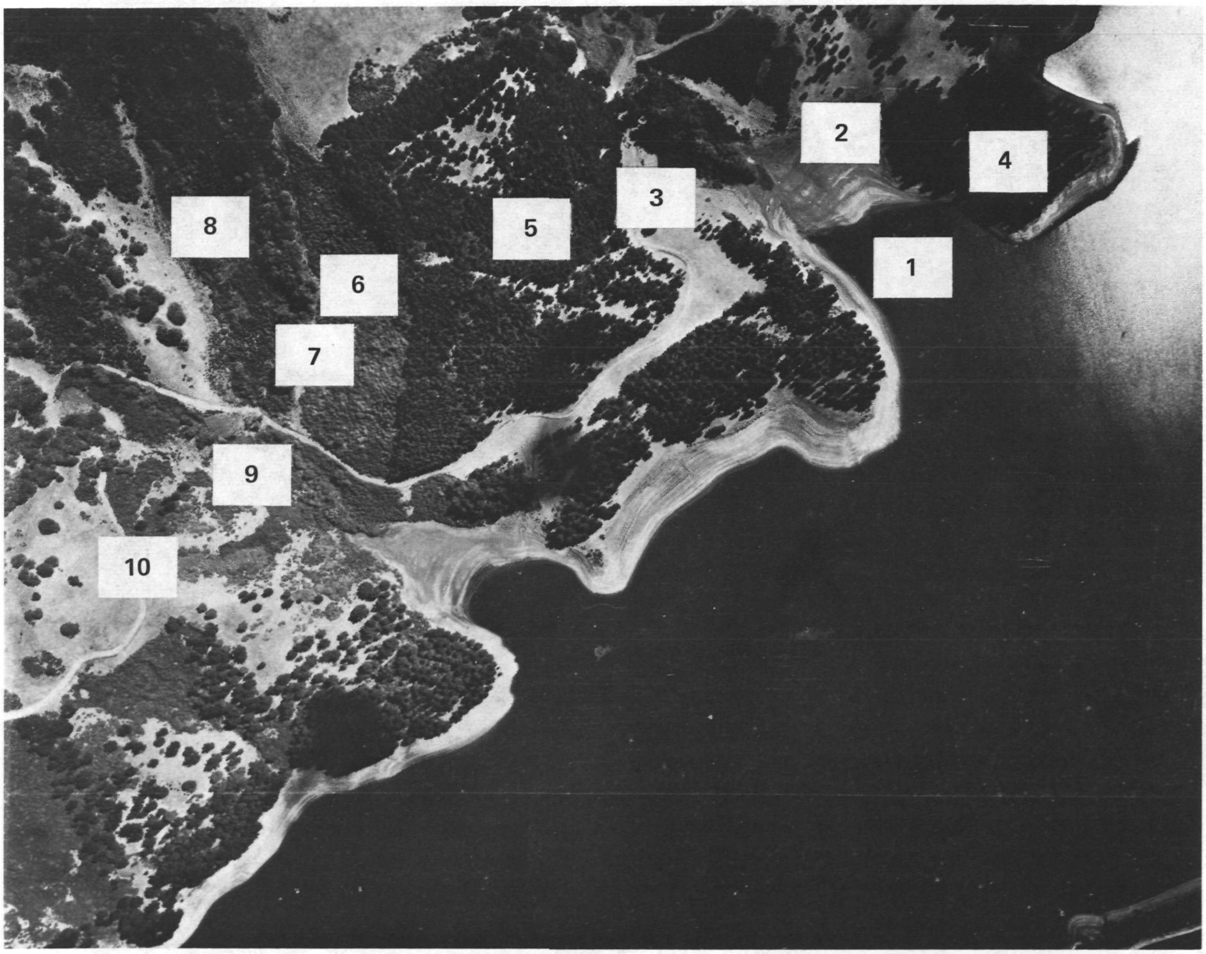

FIGURE 4. Large-scale (1:5000) photograph of portion of NASA Test Site, San Pablo Reservoir, California. (1) open water of San Pablo Reservoir; (2) shoreline hydrophytes, mainly sedges and rushes; (3) rangeland forage, mainly wild oats; (4) an old plantation of monterey pine (*Pinus radiata*); (5) a young plantation of monterey pine; (6) an admixture of poison oak (*Rhus diversiloba*) and coyote brush (*Baccharis pilularis*); (7) healthy laurel trees (*Umbelullaria californica*); (8) unhealthy coast live oak (*Quercus agrifolia*), heavily defoliated by insects; (9) a pure stand of poison oak; (10) pure stands of coyote brush.

plants is accompanied by reduced transpiration rates from the foliage with the result that there is less cooling of the leaves. In such instances the unhealthy plants, in effect, have a "fever," just as unhealthy animals frequently exhibit the same characteristic. Such a condition results in higher thermal emission from the unhealthy plants, thereby making them discernible on thermal infrared imagery (e.g., in the 8-14 μm wavelength band). Figure 5 is such a thermal infrared image of the entire San Pablo Reservoir Test Site of which figure 4 is a part. Because of the limited resolution, it is not possible to determine from figure 5 whether there is a thermal difference between healthy and unhealthy plants. However, many other interesting comparisons can be made between figure 4 (which exploits reflectance phenomena of resource features) and figure 5 (which exploits emission phenomena). Consistent with the concept of multiband reconnaissance, more information about the multiple resources within the area common to figures 4 and 5 can be discerned from a comparative analysis of the two figures than from an analysis of either of the figures alone.

Determining the Species Composition of Vegetation

Figures 6 through 10 indicate the extent to which it is possible to determine the species composition

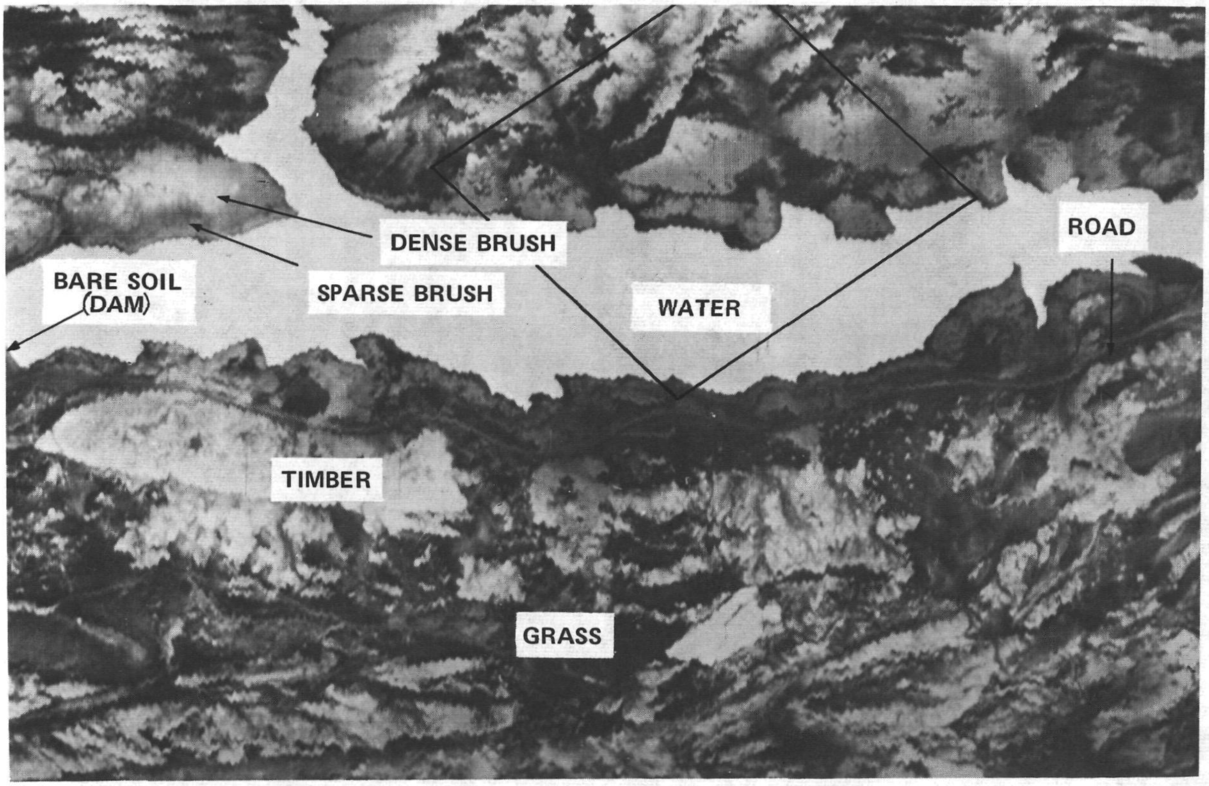

FIGURE 5. Thermal infrared imagery of the NASA San Pablo Reservoir Test Site, obtained in the 8-14 μm wavelength band from an altitude of 1500 meters at 10:00 p.m. (approximately five hours after sunset) in January 1970. Of the resource features shown here, water has the lightest tone on this positive print because, with its high specific heat and high "thermal inertia," it has cooled off the least since sunset. It is therefore warmer than its surroundings and is radiating more energy to the sensor. Areas covered by dense timber or brush appear almost as light as the water because the insulating effect of the vegetation has given these areas a high thermal inertia also. Areas of bare soil and those covered by only a thin mantle of grass already had cooled off by the time this thermogram was taken. Since such areas have little heat left to give off, they appear darkest in tone. Note that there is almost a complete reversal of tones in this thermogram as compared with the photograph (figure 4) of the area within the rectangle indicated on this figure. (Thermogram courtesy of Cartwright Aerial Surveys)

of vegetation by means of remote sensing from aircraft and spacecraft.

On large-scale aerial photos such as the one shown in figure 6 (scale 1:2500) it is possible to classify agricultural crops into six major categories or types. These six categories of crops occur not only at the NASA Davis Test Site (figure 6) but also in most other agricultural areas of the world. Once a given crop category has been identified in a particular field, reference is made to a detailed photo interpretation key which further distinguishes among the specific kinds of crops belonging to that crop category and known to be grown in the area that is being inventoried.

Even on large-scale photography it is not always possible to make positive identifications as to the specific kinds of crops, field by field. Two approaches that will facilitate this effort are the use of multiband remote sensing and the use of crop calendars.

The first of these approaches is illustrated by the radar imagery of figure 7, which serves to dif-

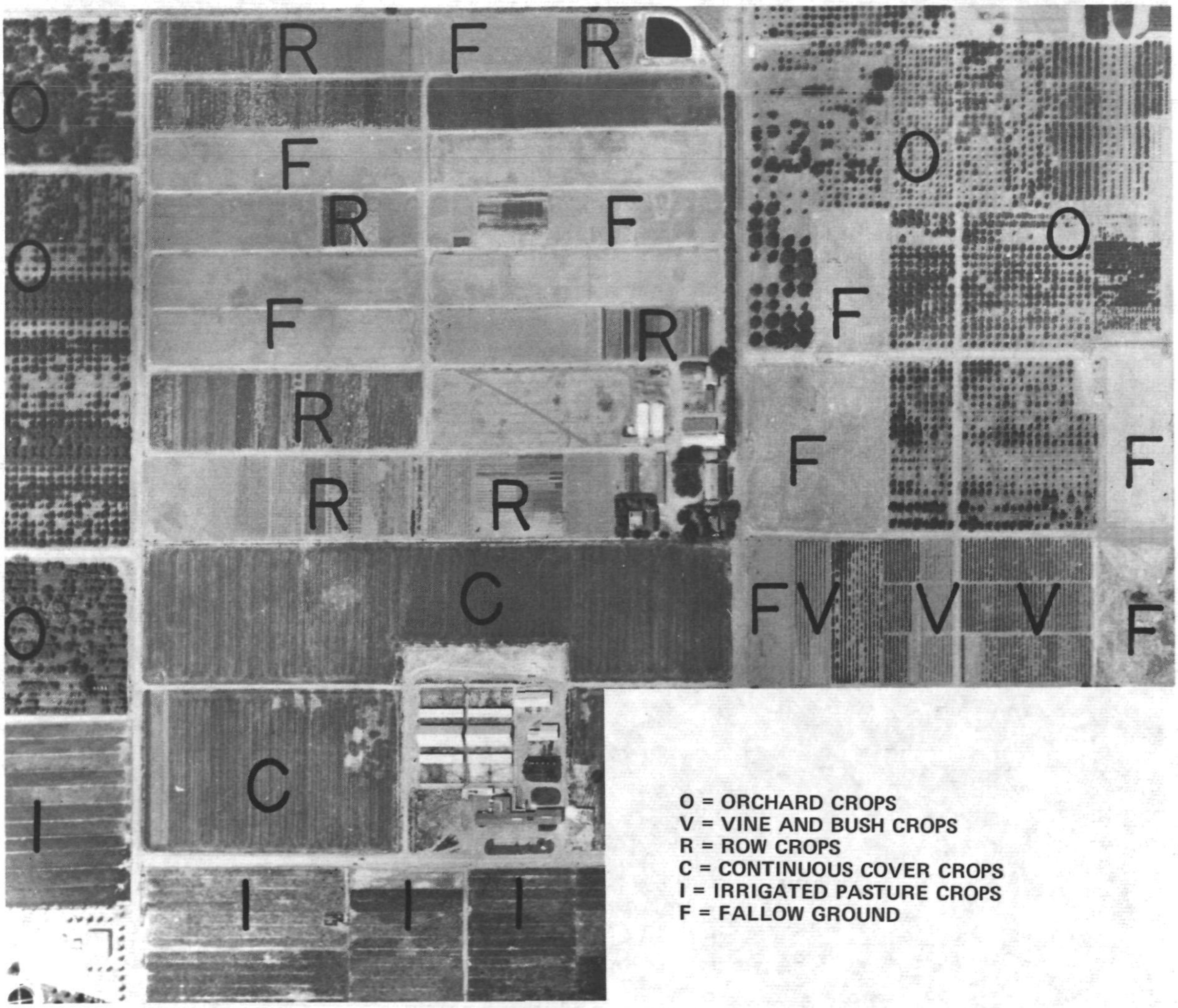

FIGURE 6. Panchromatic vertical aerial photograph of an area in California showing the six major crop types that are found in most of the world's agricultural areas. The six types can be readily recognized on photos of the quality shown here. For some agricultural areas, a detailed photo interpretation key has been constructed to assist in identifying the major crops within each of these types. Consequently, once the initial identification as to major crop type has been made, further identification as to individual species and variety of crop frequently is possible through use of the appropriate key.

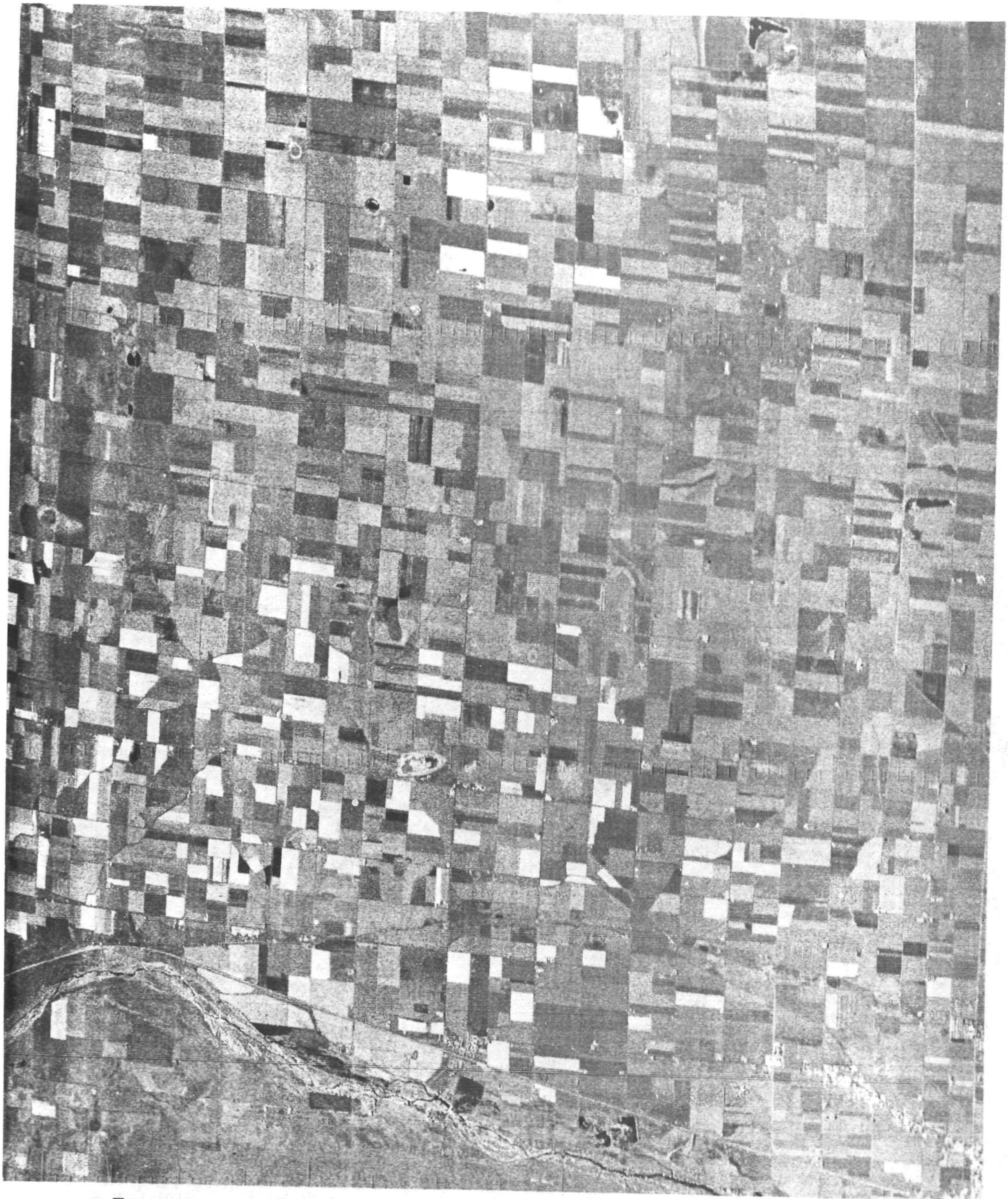

FIGURE 7. An example of K-band radar imagery taken of agricultural fields near Garden City, Kansas, in the 1-3 cm wavelength range. Light-toned fields are sugar beets. Note that on such imagery (which can be taken day or night and under nearly all weather conditions) it would be possible not only to identify certain crop types, but also to determine field shapes and field acreages. (Photos taken by Westinghouse Corporation under contract with NASA and the Army Signal Corps)

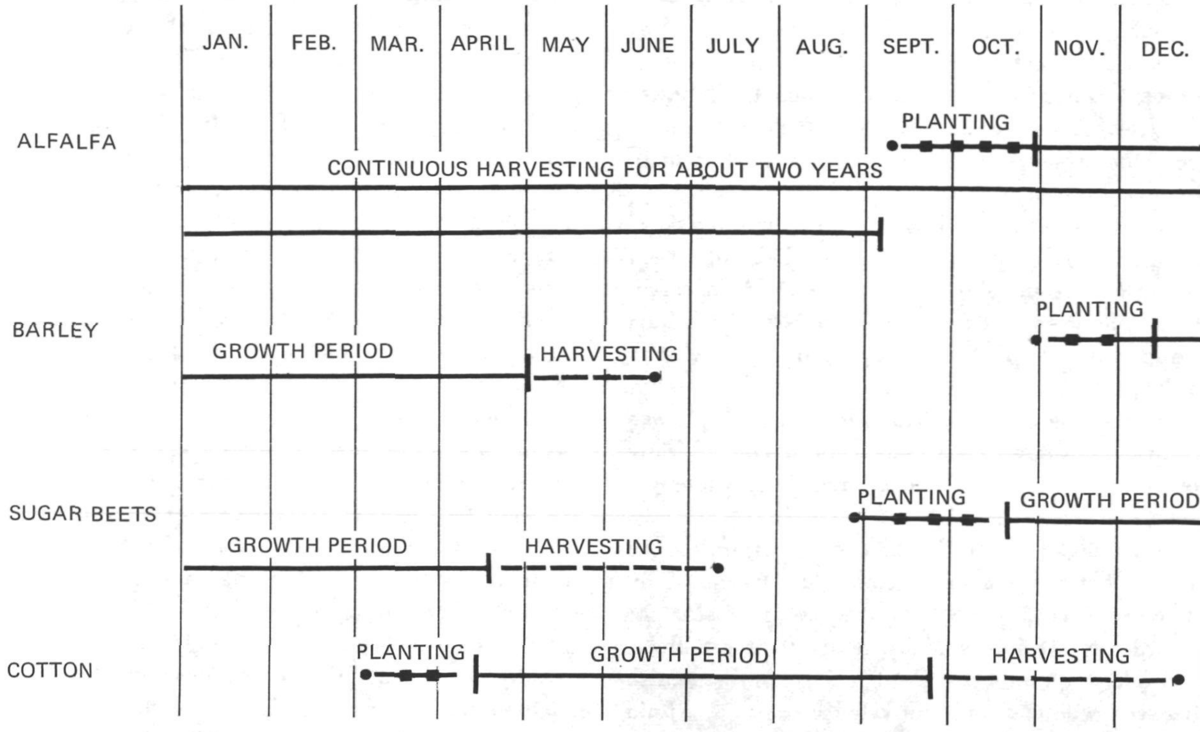

FIGURE 8. Crop calendar indicating cultivation patterns and duration of each of four major crops in the Imperial Valley test area (from Pettinger *et al.*, 1969.

ferentiate sugar beets from all other crop types or field conditions. Within the wavelength range for which most photographic films are sensitive (approximately 0.40 to 1.0 μm), sugar beet plants have essentially the same *reflectance* properties (and hence exhibit essentially the same photographic tones) as many other kinds of crops. However, sugar beet plants have unusually high *dielectric* properties, which causes them to appear brighter than most other kinds of plants on radar imagery such as that shown in figure 7.

The second approach (use of crop calendars) is illustrated by figure 8. In most instances this concept can be exploited only through the acquisition of sequential photos of the area of interest at proper time intervals during the growing season. Once this capability is assured, however, the photo interpreter may find it possible to identify crop types merely by noting the presence or absence of vegetation, field by field and date by date. When such a simplified approach is possible, sequential space photography (such as that which will be provided at approximately 17-day intervals by ERTS-A) may be

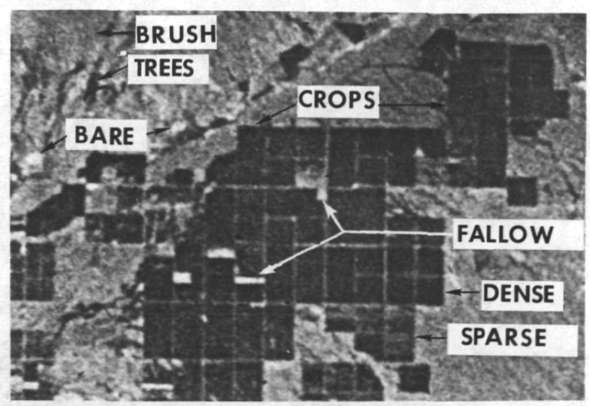

FIGURE 9. Enlargement of part of a Gemini 5 photograph taken from an altitude of approximately 200 km in August 1965. This is a black-and-white reproduction from the Ektachrome transparency. Note the ease with which one can discern the three major wildland categories (brush, trees, and bare ground) and the three agriculture field states (fallow, densely vegetated, and sparsely vegetated). Crop types are best identified on *sequential* space photography through use of a crop calendar, which merely requires photo interpretation of field state at two or three specified dates. For further details see articles by Colwell (1969) and Pettinger (1969).

adequate, at least for those fields which are of sufficient size to be clearly resolved. Figure 9, which is an enlargement of part of a space photograph taken by the Gemini 5 astronauts, indicates the feasibility of using such photography to determine the presence or absence of crops, field by field, on any given date.

Our experience to date indicates that *temporal* differences in crop types are more diagnostic than *spectral* differences. Consistent with this observation, it appears that crop types are better identified using *multidate photos taken in a single band* than on *multiband photos taken on a single date*. In either event the use of an optical combiner to form one color composite image from several black-and-white photos (see figure 10) can greatly facilitate the crop identification task.

In wildland areas the task of determining the species composition of vegetation by means of remote sensing often entails the use of *multistage* techniques. As indicated by figure 9, it usually is possible, even on space photography, to distinguish between wildland and cultivated areas and, within the wildland areas, those portions that are forested, brush-covered, or grass-covered. This fact is further illustrated by the stereo pair of space photos comprising figure 11. Space photography, by providing an overall view of the entire area to be classified, permits a 100-percent delineation of the major wildland types and contributes the first stage in a multistage sampling scheme, even though it may provide resolution of only 100 to 150 meters. Such photography may merely permit one to *discriminate* between features and thus draw accurate boundaries to separate them. What also is needed is accurate *identification* of resource features on either side of the boundary. It is for this reason that closer looks are needed at representative areas, through the multistage sampling process.

For the second stage, photography of much higher resolution (e.g., 1 to 1.5 meters) usually is required (see figure 12), but only of representative areas selected from a study of the first-stage space photography. And for the third stage, photography of still higher resolution (e.g., 7 to 12 cm) usually is required (see figure 13), but only of still smaller areas selected from the second-stage photography.

Often the viewpoint is advanced that the complexities of multisage sampling (moderate though they are) could be eliminated if only it were pos-

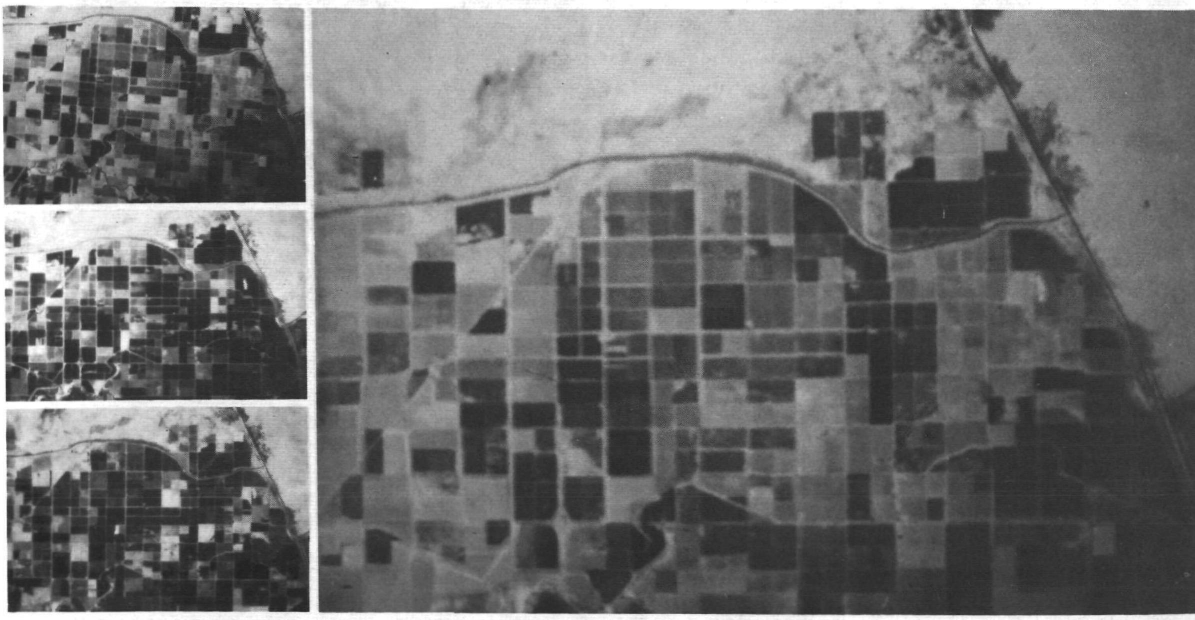

FIGURE 10. On the left are three Pan-25A photos of an area in Imperial Valley, California, taken from an altitude of 20 km in March, May, and August, 1969. On the right is a color composite made from these three photos using an optical combiner. Because of the crop calendar concept, a unique "color signature" is thus produced for each crop type, as discussed in the text.

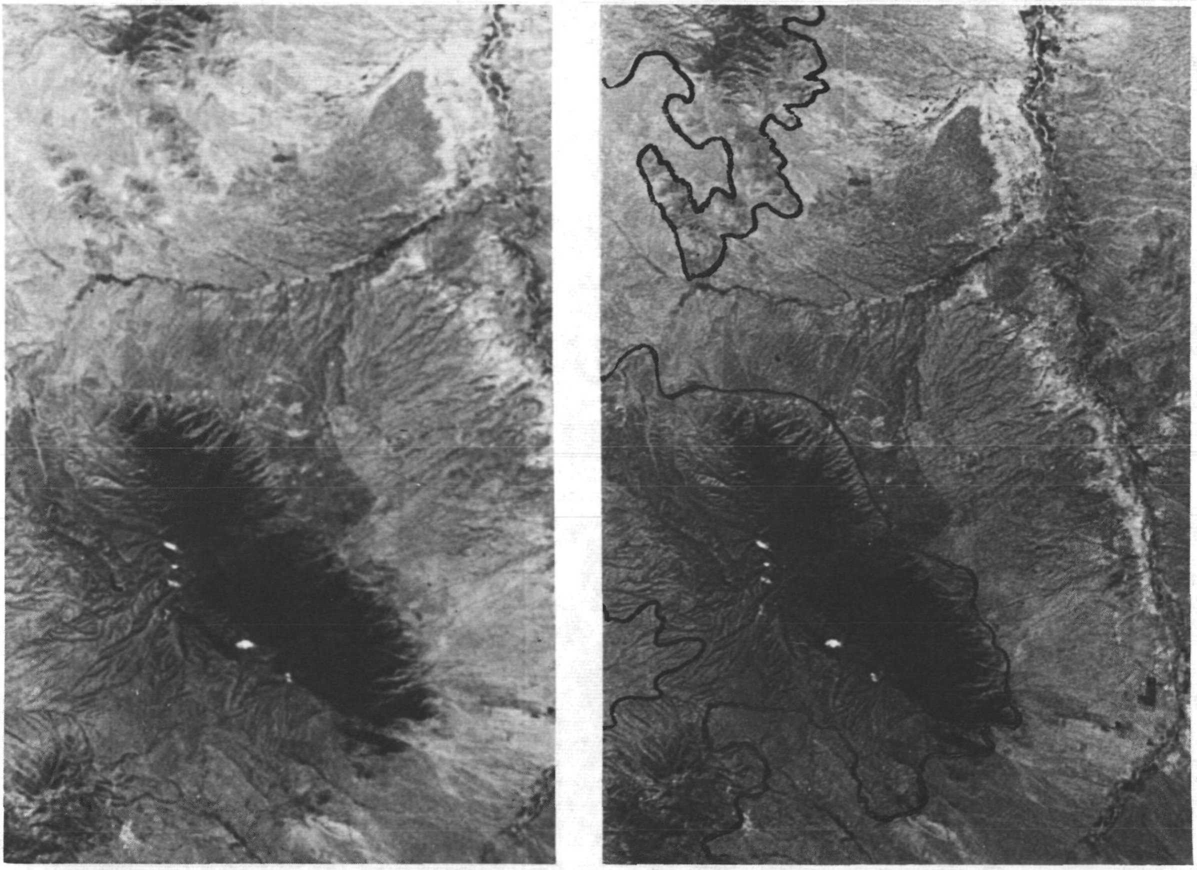

FIGURE 11. Stereo pair of space photographs of an area in southern Arizona on which the three major vegetation/terrain conditions are readily delineated: (1) nearly flat terrain with white thorn, tarbrush, and creosote brush; (2) hilly terrain with mesquite along draws and a sparse cover of mixed xerophytes elsewhere; and (3) mountainous terrain mainly with an oak woodland/juniper/chapparal vegetation cover. Compare outlined area with large-scale photos of figure 14.

sible to have high-resolution imagery of the entire area that is to be inventoried. Then, it is argued, there would be no need for imagery of moderate to low resolution. In evaluating this viewpoint we may find it helpful to compare that part of the low-resolution space photos appearing in figure 11 with the same area as imaged on the much higher-resolution aerial photo of figure 14. On so doing we will find, as in countless other instances, that the important major resource boundaries are delineated as accurately on the low-resolution space photos as on the high-resolution aerial photos. Furthermore, experience has shown that on the space photos those major boundaries are delineated more consistently throughout a vast area, especially if more than one photo interpreter is involved in the task. In any multistage sampling scheme this factor of consistency of category delineation assumes very great importance. In addition, a comparison of figures 11 and 14 will clearly show that such boundaries can be delineated much more quickly on the space photos than on the aerial photos.

Determining Changes in Land Use and Resource Status

The foregoing examples have indicated the feasibility of using remote sensing techniques to determine for any given date the land use and resource status for each portion of the area that is being inventoried. Certain advantages also have been

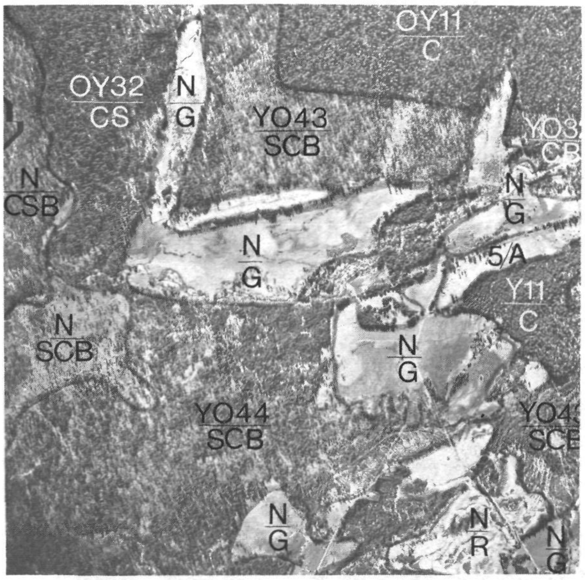

FIGURE 12. Photo interpretation of this forested area has permitted it to be "stratified" into essentially homogeneous units as regards (1) age class of timber (left half of numerator), e.g., O=old; Y=young; (2) density of sawlog-size timber (first digit of numerator) and of all timber regardless of size (second digit), e.g., 1 signifies 80 to 100 percent of ground is covered by crowns of trees; (3) vegetation elements present (denominator), e.g., C=commercial conifer; H=hardwood, etc.; N in numerator indicates nontimber site; i.e., soil too poor to grow timber at a sufficiently rapid rate for commercial purposes.

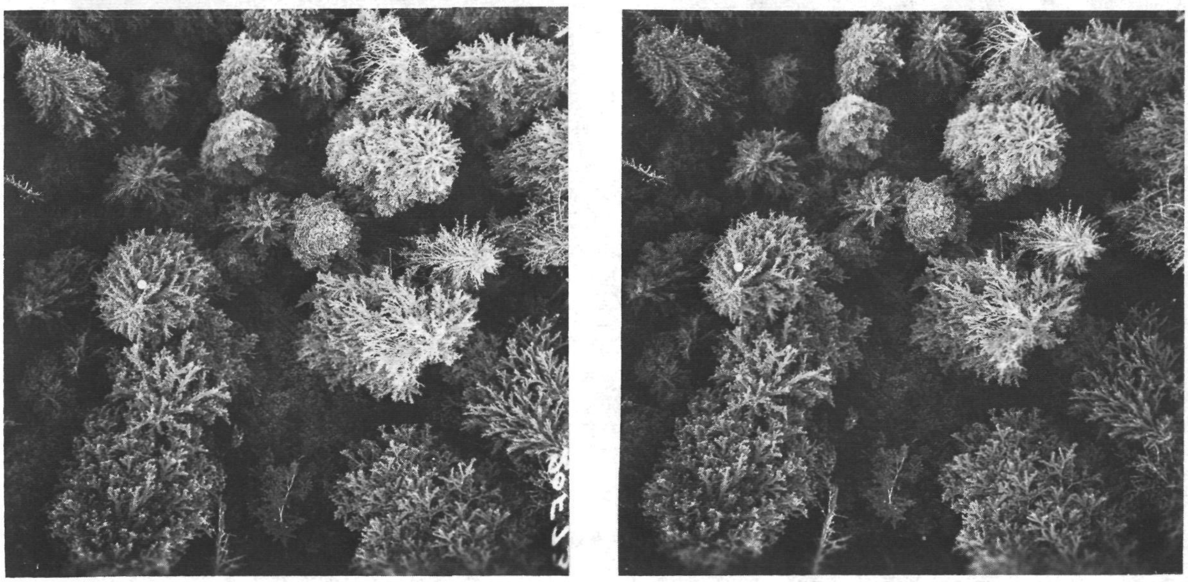

FIGURE 13. On this large-scale vertical stereogram taken from a helicopter, the most important tree species (fir, cedar, and hemlock) are accurately identifiable. Tree heights frequently can be determined more accurately from stereoscopic parallax measurements on photos such as these than from conventional on-the-ground measurements made with an Abney level or other hypsometer. As seen near the left center of this stereogram, a small gas-filled balloon raised from the ground to slightly above treetop level facilitates the location of sample plots such as this by the helicopter pilot and photographer. By image comparison, the photo interpreter can extrapolate information he has obtained from large-scale photography such as this and apply it to sizable adjacent areas of similar appearance for which only small-scale photography is available. (Photos courtesy of E. H. Lyons and the British Columbia Forest Service)

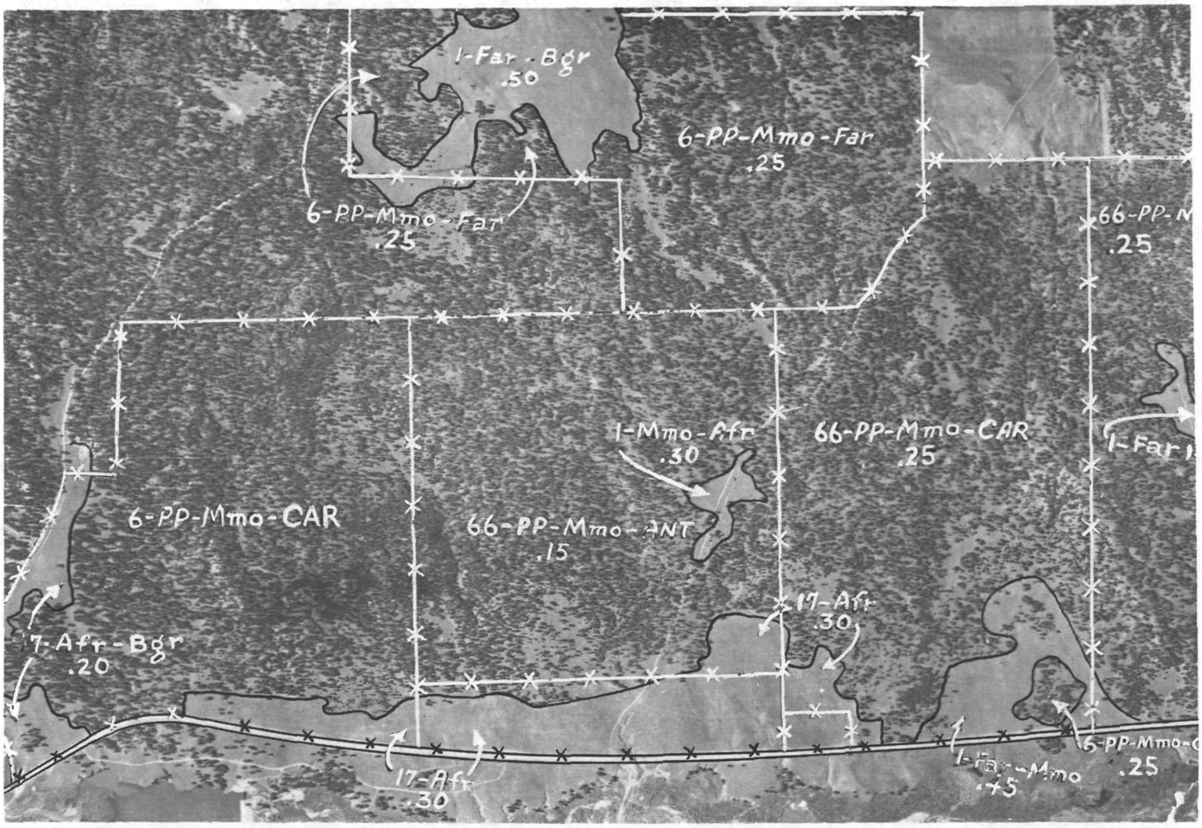

FIGURE 14. Photo interpretation and associated field work have enabled the range surveyor to stratify this area into essentially homogeneous units. Lines with crosses represent fences, lines without crosses represent type boundaries. Within each stratum a hand-drawn symbol appears which gives three types of information: (1) the range type (e.g., 1 signifies grassland other than meadows, 6 signifies coniferous timber land with an understory of forage plants, etc.); (2) the most abundant species (e.g., Far signifies fescue grass (*Festuca arizonica*), PP signifies ponderosa pine, etc.); (3) the vegetation density (e.g., .25 signifies that 25 percent of the ground surface is covered with vegetation). (Courtesy of U.S. Forest Service)

indicated for use of a technique based on the "comparative analysis" of "sequential photography."

These same concepts can be applied in determining (1) the extent to which forest land is being converted to agricultural land (top half of figure 15) and (2) the extent to which agricultural land is being converted to urban development (bottom half of figure 15). In addition, the nature of plant succession on the degree of acceleration of soil erosion that is induced by various resource management practices can be determined by such means. Examples of the latter will be found in a separate paper (Colwell, 1969).

The value of being able to make such observations through the proper use of remote sensing techniques can scarcely be overemphasized. Too often we tend to regard a resource inventory as an end in itself. Again, we must remind ourselves, therefore, that the ultimate objective is *better resource management* through the previously described three-step process (inventory, analysis, and operations). Once we know the changes in land use and resource status that are brought about through various resource management practices, we can determine the courses of action which the resource manager should follow, area by area, in the future to achieve the most desirable changes.

Planning Engineering Activities That Will Lead to Resource Development

Construction engineers can interpret aerial photos, space photos, and other forms of remote sensing

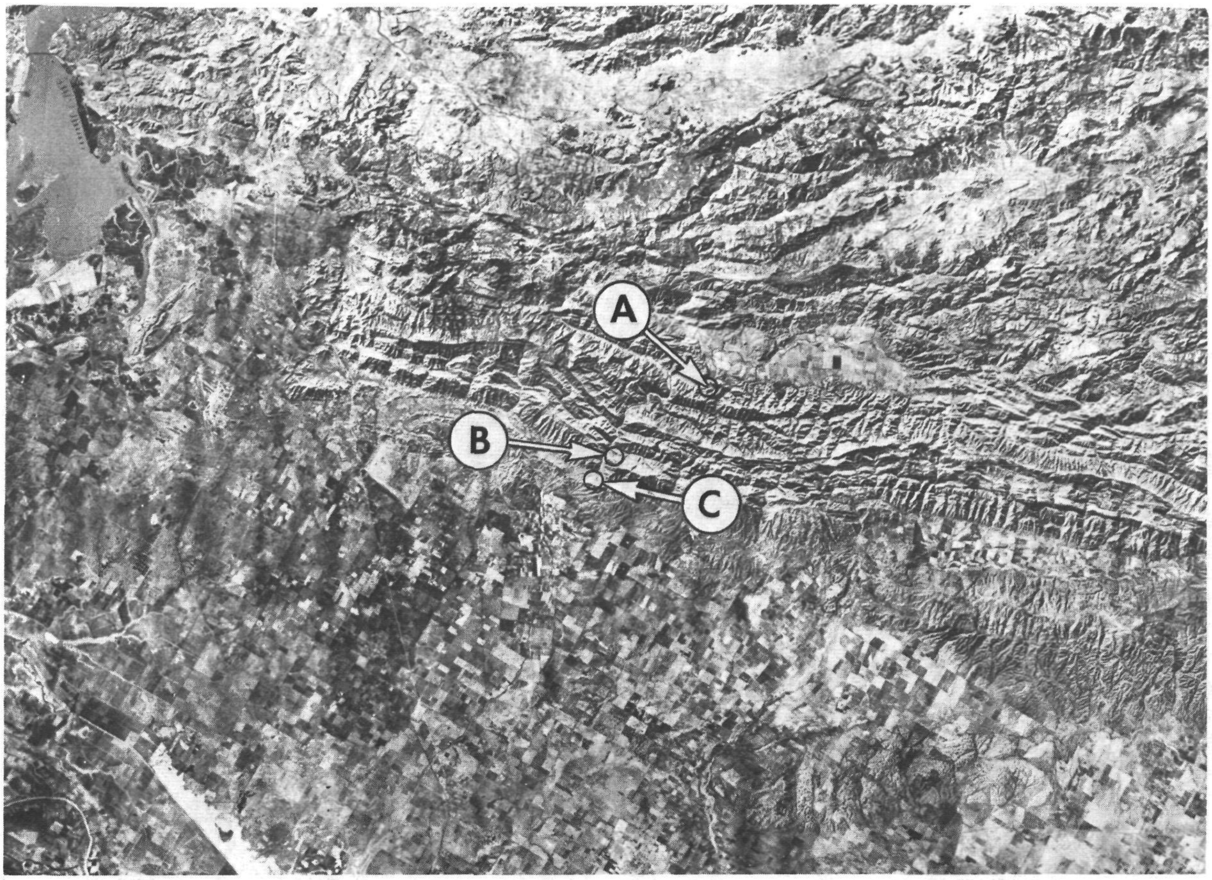

FIGURE 15. For a discussion of how a space photo such as this can be analyzed for resource development, see text.

data to aid in selecting sites for dams, levees, and other water control structures; laying out highways, airfields, canals, and pipelines; and otherwise planning for full exploitation and wise management of agricultural and wildland resources. Since they are interested in land forms, rock materials, soils, vegetation types, and drainage conditions, much of what has already been discussed is as applicable to engineering as to agriculture and forestry.

Figure 15 provides an excellent illustration of how the engineer might use satellite photography to help solve an important engineering problem. The mountainous areas shown here have moderately high rainfall, probably 75 to 125 cm per year, judging from the presence of dark-toned woody vegetation and the numerous stream channels. Nearby are large fields in rectangular pattern, without deeply incised drainage; these fields must be moderately flat and, judging from the size of the individual fields, must be planted to dry-land crops. This combination of conditions suggests that the soil is fertile and that food production would be increased if water could be impounded in a reservoir and used to irrigate the fields. Further study of the photograph reveals that a large stream is constricted in a deep canyon at point A. Here a dam could be built, converting the mountain valley immediately upstream into a large reservior. This valley does not appear to be densely populated, so the property could probably be acquired at reasonable cost. The watershed draining into this mountain valley is large enough to supply ample water to the proposed reservoir. Since the canyon at point A is deep, a dam built there probably would create a waterfall sufficient to generate great amounts of hydroelectric power. There appears to be a rapid fall in the stream from the proposed site to nearby point B. From this point water might be fed into a second

power plant at C. Closer study, however, shows that this part of the plan would not be feasible, because the water conduits would have to traverse many deep canyons between points A and B.

The top half of figure 15 shows alternating mountains and valleys. When this area is studied according to the criteria just mentioned, however, topography and culture are seen to be unfavorable for dam construction, crop irrigation, and hydroelectric development.

The interpretation described here was made quickly and easily because the entire area pertinent to the analysis was imaged on a single photograph. The interpretation has been confirmed since the photographs were taken. Each development recommended by the photo interpreter has been made; each development considered by him, but dismissed as not feasible, was independently dismissed by engineers making ground studies. Of course, the photo interpreter's recommendation of a dam or other construction site must be carefully checked on the ground before a final decision is made.

A photograph such as figure 15 could also be used to lay out possible routes for a proposed highway, railroad, or pipeline. Once the possibilities are delineated, large-scale photography would, of course, be needed of the two or three most promising routes. The final selection of the route would entail property valuation, estimation of cut and fill, and determination of soil, rock, and drainage characteristics, all of which could be made with large-scale photography combined with only a limited amount of groundwork. Thus, we see in this example another opportunity to exploit the concept known as multistage sampling.

SUMMARY AND CONCLUSIONS

In this paper, an attempt has been made to (1) express the rationale that prompts our present great interest in possible applications of remote sensing in agriculture and forestry; (2) categorize and tabulate the various user requirements for information on agricultural and forest resources; (3) outline general procedure, based on the use of remote sensing data, that has proved highly workable on many occasions when inventories were to be made of agricultural and forest resources; (4) list and discuss both the advantages and limitations currently associated with the use of aerial and space photographs for the evaluation of agricultural and forest resources; and (5) provide numerous specific examples of remote sensing uses in agriculture and forestry.

Based on information contained in this paper and in the works listed in the bibliography, the following conclusions seem justified: (1) Rarely is all the resource information that is desired by an agriculturist or forester obtainable from examination of a single photograph covering the area which he seeks to manage; (2) *multiband* photography provides more information than is obtainable from only one band; (3) *multidate* photography provides more information than is obtainable from only one date; (4) *multistage* photography provides more information than is obtainable from only one stage; (5) *multi-enhanced* photography provides more information than is obtainable from only one enhancement; (6) *multipurpose* and *multiresource* studies, made by a *multidisciplinary* panel of experts, provide more information than single-purpose, single-resource studies made by one individual who is expert in only one discipline; and (7) collective gains realizable through all the above-mentioned concepts make it possible to apply remote sensing techniques in a highly effective manner in almost every situation where the primary objective is to manage agricultural and forest resources as wisely as possible.

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Remote Sensing Oceanography

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The development of remote sensing technology has had a logical extension to studies and investigations of the world's oceans. Such sensors are capable of providing an overview of surface or immediate subsurface conditions in near-real time. For this reason remote sensors are customarily related to the role of synoptic data collection, or in the context of this paper to "synoptic oceanography."

The collection of ocean-related data on a synoptic basis is important because the hydrosphere covers approximately 70 percent of the Earth's total surface. For many applications the overview can be as important as detailed data collected at a single location. The development of remote sensing techniques, when related to satellite platforms, offers potential coverage of the world's oceans on a global basis, which is an important aspect when the deployment of other types of data collection platforms is considered.

It should be recognized that remote sensing technology does not replace *in situ* data collection techniques that are used and continually being improved. Indeed, it appears that the use of remote sensors may require quite stringent *in situ* measurements to permit full interpretation of the remotely collected data. To illustrate this feature, note that sea surface temperature can be measured *in situ* simply with a bucket and thermometer, while the use of a remote sensor for this measurement requires the measurement of not only the surface temperature but also the effects of the atmosphere. A further complicating factor in using remote sensors is that many phenomena can alter the signature of the data that would not affect an *in situ* measurement. For example, a wave staff can measure wave height of gravity waves, but certain remote sensors that would measure wave height are further influenced by the capillary wave structure. Such an occurrence can be beneficial, but it nevertheless increases the requirement for *in situ* measurements for capillary structure in concert with the remotely sensed data.

Another aspect in developing remote sensors for ocean studies is that the remote sensing oceanographer cannot isolate the single event he may wish to measure and ignore the others. As an example, if one wishes to measure chlorophyll concentration *in situ*, it is a relatively straightforward experiment, while the same measurement made with a remote sensor requires that data on surface roughness, Sun angle, cloud cover and atmospheric conditions, bottom type in shallow water, and other water components such as sediment load, etc. be measured in order to analyze and interpret the data.

Once a full interpretation of remotely sensed data is quantitatively established, then not only can a chlorophyll measurement be made, for example, but many other related features may be measured as well. Hence, by using a limited number of regions of the world for development, test, and calibration of sensors, the technology can be extended to other regions of the globe until a research satellite can collect these data on a global basis. The original test and calibration sites may then be used to verify the satellite operations.

The primary types of remote sensors presently being applied to studies of the world's oceans are acoustic, electromagnetic, gravity, and magnetic. This paper will be limited to the potential applications of electromagnetic sensors to studies of the oceans.

AREAS OF FEASIBLE APPLICATION

The objectives of the remote sensing program in developing space techniques for ocean data collection fall into the following four general categories:

(1) To identify, test, and evaluate techniques which can be used on Earth survey spacecraft to provide meaningful and useful synoptic oceanographic data.

(2) To establish the reliability of spacecraft-acquired oceanographic data by comparison with remotely sensed surface data and relate these data to surface and subsurface ocean phenomena.

(3) To develop and test techniques of displaying space-acquired data on a global basis consistent with conventional synoptic data.

(4) To develop environmental forecasting techniques for dynamic ocean phenomena using space-acquired data.

In establishing the feasibility of concepts for potential space systems, several platforms have been used or are planned for use in the remote sensing

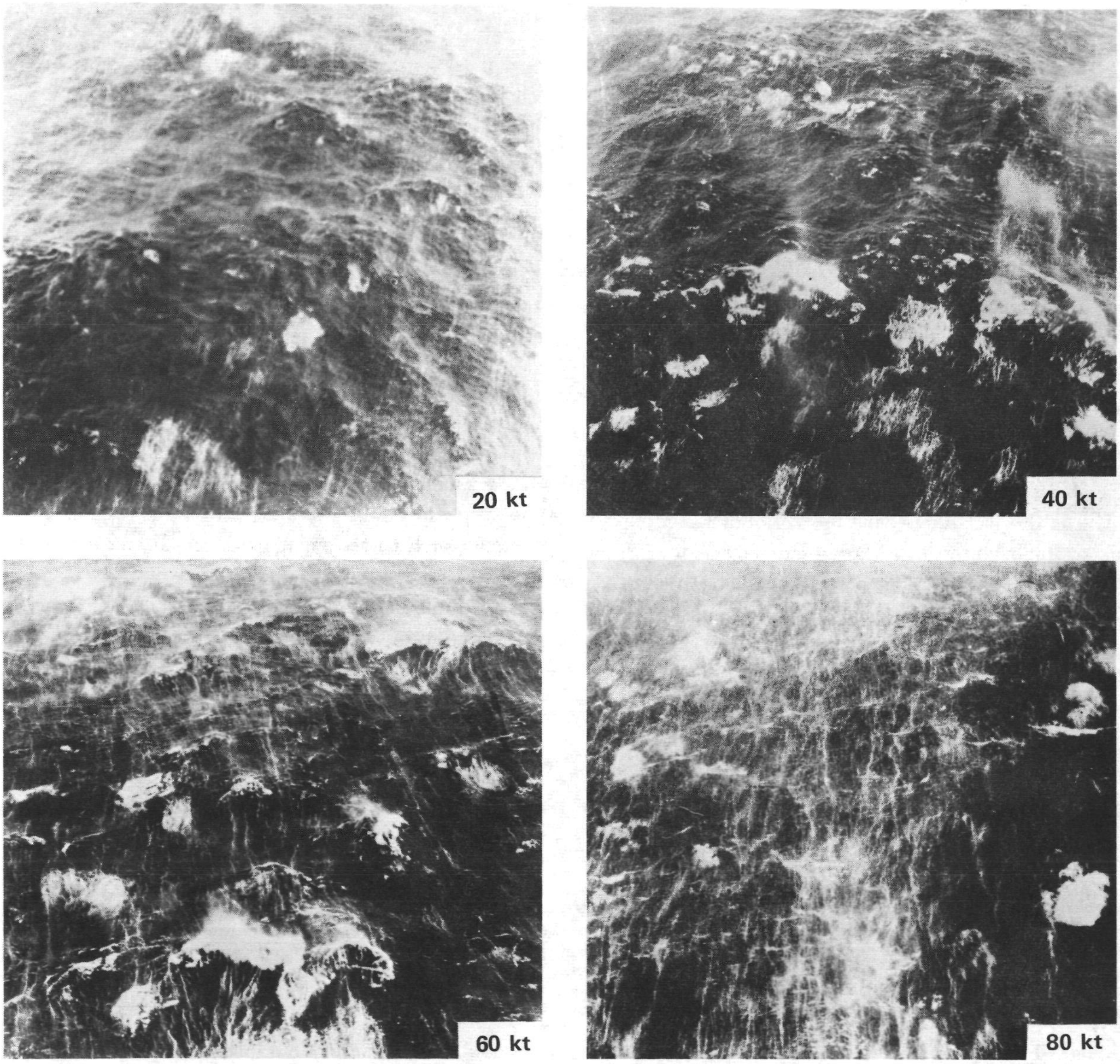

FIGURE 1. Photographs of the surface of the ocean subjected to surface winds of 20, 40, 60, and 80 knots. Photos by Naval Air Station, Jacksonville, Florida (from ref. 1).

studies of the oceans. These include fixed piers and towers, submersibles, buoy systems, ships, and aircraft. These platforms are capable of providing useful ocean data in themselves and should not be regarded as mere stepping stones to a space system. Each platform can contribute uniquely to our understanding of the oceans and will remain as basic components in a deployed research space system.

PROPERTIES OF THE OCEAN

There are two fundamental properties of the ocean surface that must be understood by anyone studying the ocean with electromagnetic sensors. These are the roughness features of the ocean surface and the penetration of electromagnetic energy into water.

The surface of the ocean is highly variable. It can be a mirror-smooth surface acting as a specular scatterer under calm conditions, or an extremely dangerous mass of white water when driven by high winds for an extended period of time. Figure 1 (from ref. 1) illustrates how the ocean surface appears from an altitude of approximately 150 to 250 meters at an angle of about 45° when driven by winds of 20, 40, 60, and 80 knots (approximately 10, 20, 30, and 40 m/s).

Because of the inherent danger to those who must ply the seas, remote sensors are being developed to measure and, with appropriate data processing, predict the conditions of the ocean surface under all weather conditions. The all-weather capability is important because turbulent surface conditions are often accompanied by storm and cloud systems, which must be penetrated for surface measurements. Thus, while glitter pattern analysis from visible-region remote sensors can permit measurement of surface roughness in cloud-free areas, cloudy conditions require the use of either active or passive microwave sensors to make the roughness measurement. Microwave energy is attenuated much less by clouds than is electromagnetic energy in the visible and thermal regions of the spectrum.

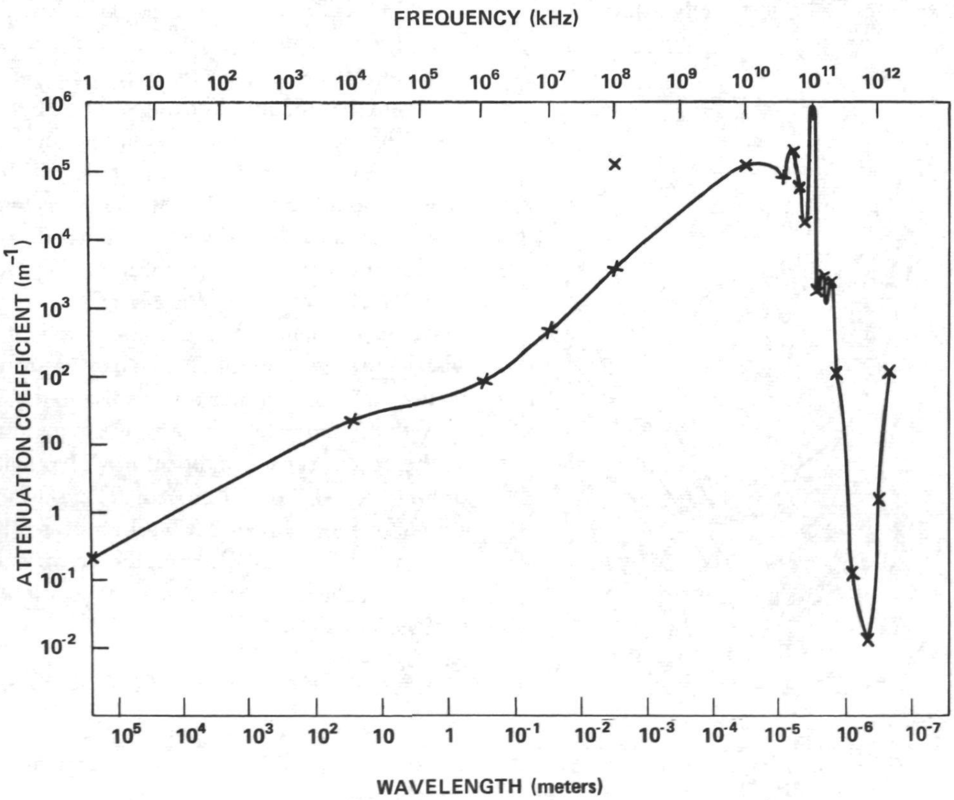

FIGURE 2. Attenuation coefficient vs. wavelength and frequency for seawater (from ref. 2).

The second essential property of the oceans is the manner in which electromagnetic energy can penetrate water. The degree to which radio waves, microwaves, thermal energy, and visible light are attenuated is shown in figure 2 (data taken from ref. 2). Note that significant water penetration occurs only in two general regions of the spectrum: at very low frequencies on the order of 1 kHz (wavelength about 300 km) and at a frequency of about 7×10^{11} kHz (wavelength about 0.45 μm). Because it is impractical to build remote sensors to operate at the very long wavelengths, the only portion of the spectrum where significant penetration is possible with remote sensors is the blue-green portion of the visible band from 0.4 to 0.6 μm.

Figure 3 shows the attenuation coefficient of several types of water at wavelengths of 0.35 to 0.70 μm. Mean oceanic water is only slightly more attenuating than distilled water in this portion of the spectrum, so that energy in the blue-green (0.45 to 0.55 μm) region is attenuated by $1/\epsilon$ in a distance on the order of 10 to 20 meters, while in the red region this distance is reduced to only a few meters.

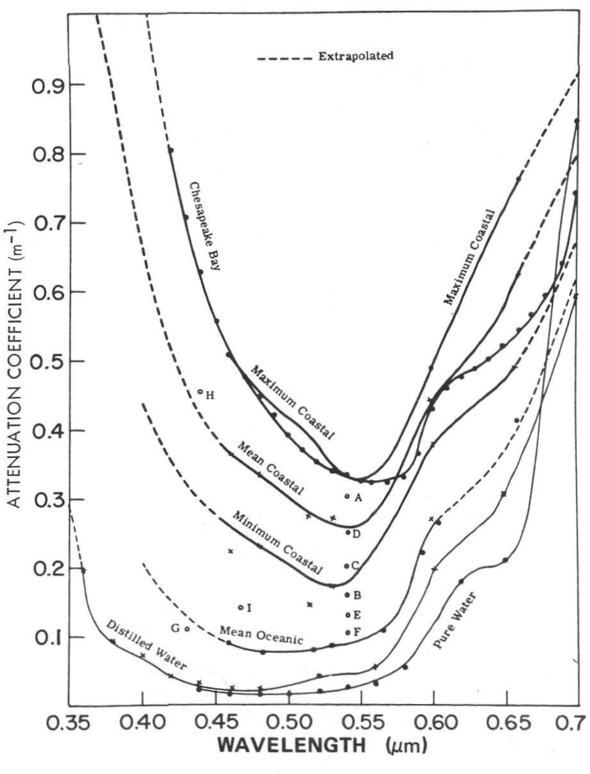

FIGURE 3. Visible region attenuation coefficient vs. wavelength for pure water and seawater (from ref. 2).

A further feature shown in figure 3 is the shift in the region of maximum penetration from the blue to the green region as the water changes from that typical of the open ocean to that found in the coastal area. Thus, depending on the type of ocean water, there may be a preference in the portions of the visible spectrum to be used. The response of light energy interacting with the ocean can be illustrated on a qualitative basis by using a four-band multispectral camera with filters covering the blue, green, red, and a combination blue and green as shown in figure 4. These filters were used to photograph simultaneously the *Ben Franklin* submersible used by Dr. Jacques Piccard prior to his 30-day cruise in the Gulf Stream during the summer of 1969 (ref. 3). Figure 5 shows photographs of the *Ben Franklin* at the ocean surface, taken in each of the bands of figure 4. The deck was painted with a gray, spectrally flat paint, and the conning tower was yellow. The shroud tubing (located fore and aft on each side), which protected the four small propellers used for maneuvering, can be seen in figure 5. As shown in figures 6, 7, and 8, the *Ben Franklin* was photographed in Gulf Stream water (typical of mean oceanic water in figure 3) at depths of 10, 15, and 25 meters. At a 10-meter depth the submersible is not visible in the red band, whereas even the shroud tubing is still distinguishable in the other three bands. At 15 meters the contrast is sufficiently reduced to obliterate the shroud feature, but the conning tower is still distinguishable. At 25 meters the *Ben Franklin* is still visible in all three bands, but the contrast is reduced to where only the general outline can be seen, with the features of the conning tower obscured.

With an understanding of these general properties of the ocean, several applications of remote sensing techniques will be discussed. The sensors can be simple or more advanced, but in all cases the remote location of the sensor above the ocean surface provides significant advantages not available from a surface location.

FISHERY ENVIRONMENT ASSESSMENT

The detection of fish and the given environmental conditions in which a particular species of fish is most likely to be found have been shown to be amenable to remote sensing applications in several studies (ref. 4, 5, 6). Studies of the direct detection

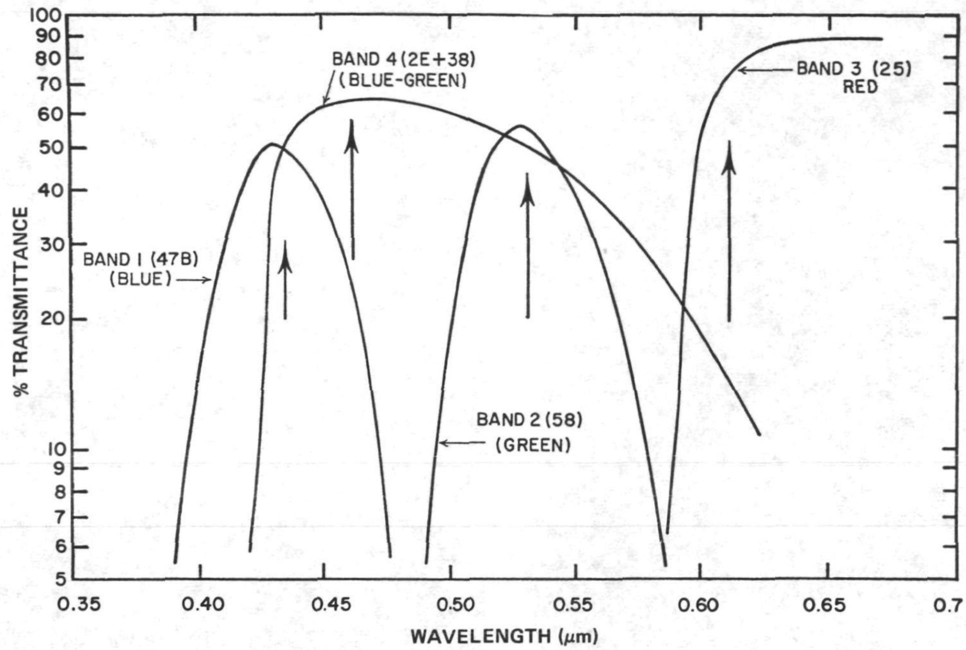

FIGURE 4. Typical transmittance of filters used in oceanographic research (from ref. 3).

of fish include spectrometer measurement of fish oils, photography of schooling fish for behavioral analysis, spectral and fluorescent properties of fish, and bioluminescence displays resulting from excitation of light-producing plankton by the mechanical motion of swimming fish. The environmental conditions to which fish are known to correlate include both temperature and water-mass/ocean-color characteristics.

It is not necessary to operate expensive remote sensors to assist in the detection and capture of fish. The human eye and brain, being quite sophisticated as a sensor and data processor, can be used to great advantage as a remote sensor when trained. The vantage point of a man in a crow's nest has been extended to that of a man in a spotter aircraft with radio communication to the fishing vessel or vessels. Using such data as water discoloration and known locations of fish on a previous day, a spotter searches for a given species of fish. Upon successful detection of a fish school, the spotter may further assist in the acquisition of the fish by directing the laying of nets. While simple in concept, this is a proven application of a man operating from a vantage point giving improved search capability.

The other forms of fish detection are all dependent on daylight, except stimulated fluorescence and observation by bioluminescence emission. Stimulated fluorescence has not been fully explored, even in the laboratory, while the detection of bioluminescence phenomena has been demonstrated from aircraft. Bioluminescent organisms appear to be distributed throughout the world's oceans and are most abundant where nutrients are the highest. A typical emission spectrum is shown in figure 9 (from ref. 7). Under ordinary circumstances these emissions are too weak to be seen by the unaided eye. However, the development of image intensifiers has extended the eye's capability to operate at low light levels. As a result, it appears feasible to extend the spotter pilot's role to include nighttime operation with a sensor called a low-light-level television system. The view that a spotter pilot might have on a moonless night from about 1 km altitude is shown in figure 10. The school has excited the bioluminescent organisms into radiating very low levels of light energy, thus outlining the school. Such systems appear at present to be oriented toward aircraft rather than spacecraft, offering a relatively inexpensive means of extending the period of time to search for fish.

The assessment of the fishery environment calls

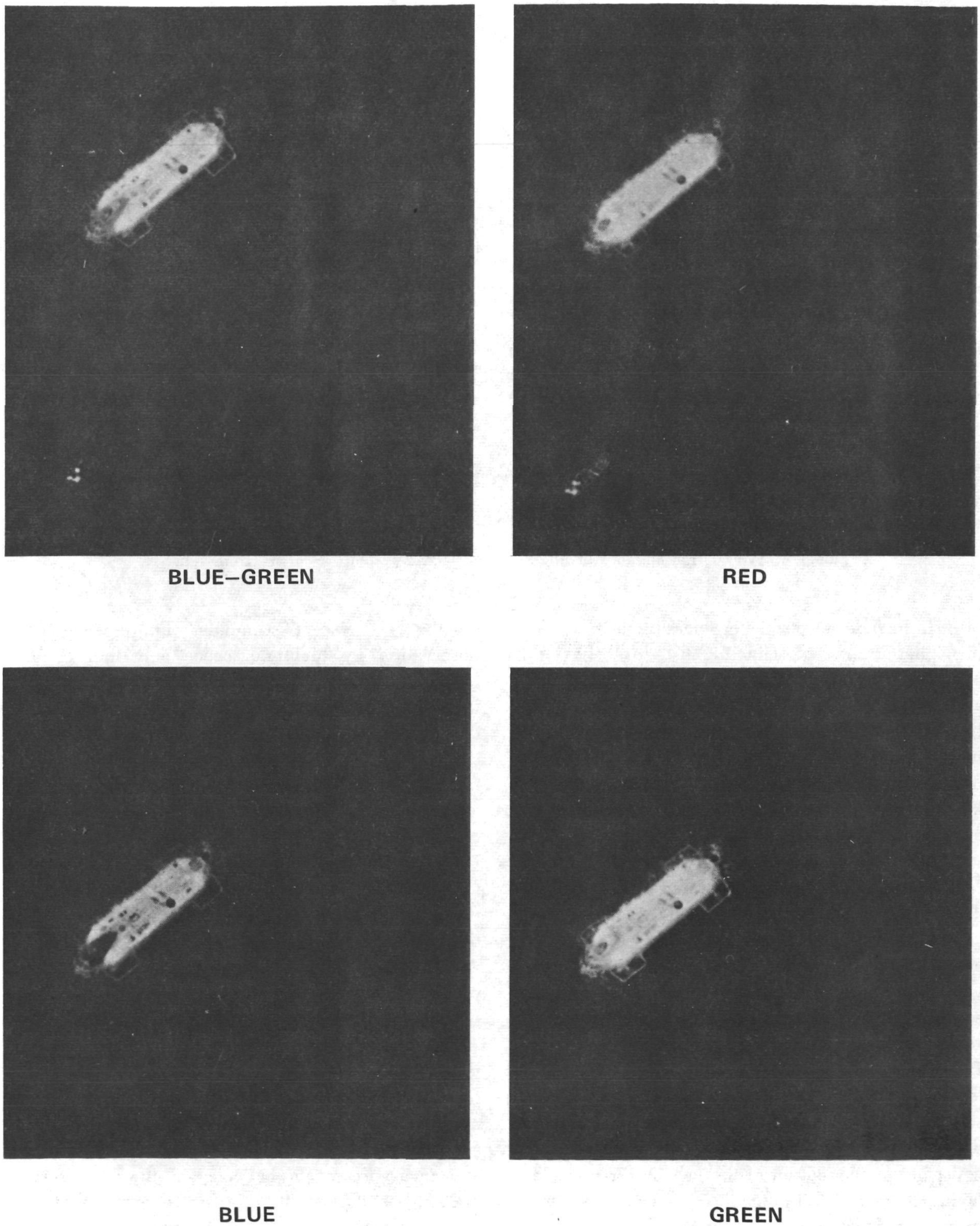

FIGURE 5. Multispectral photography of *Ben Franklin* on surface (from ref. 3).

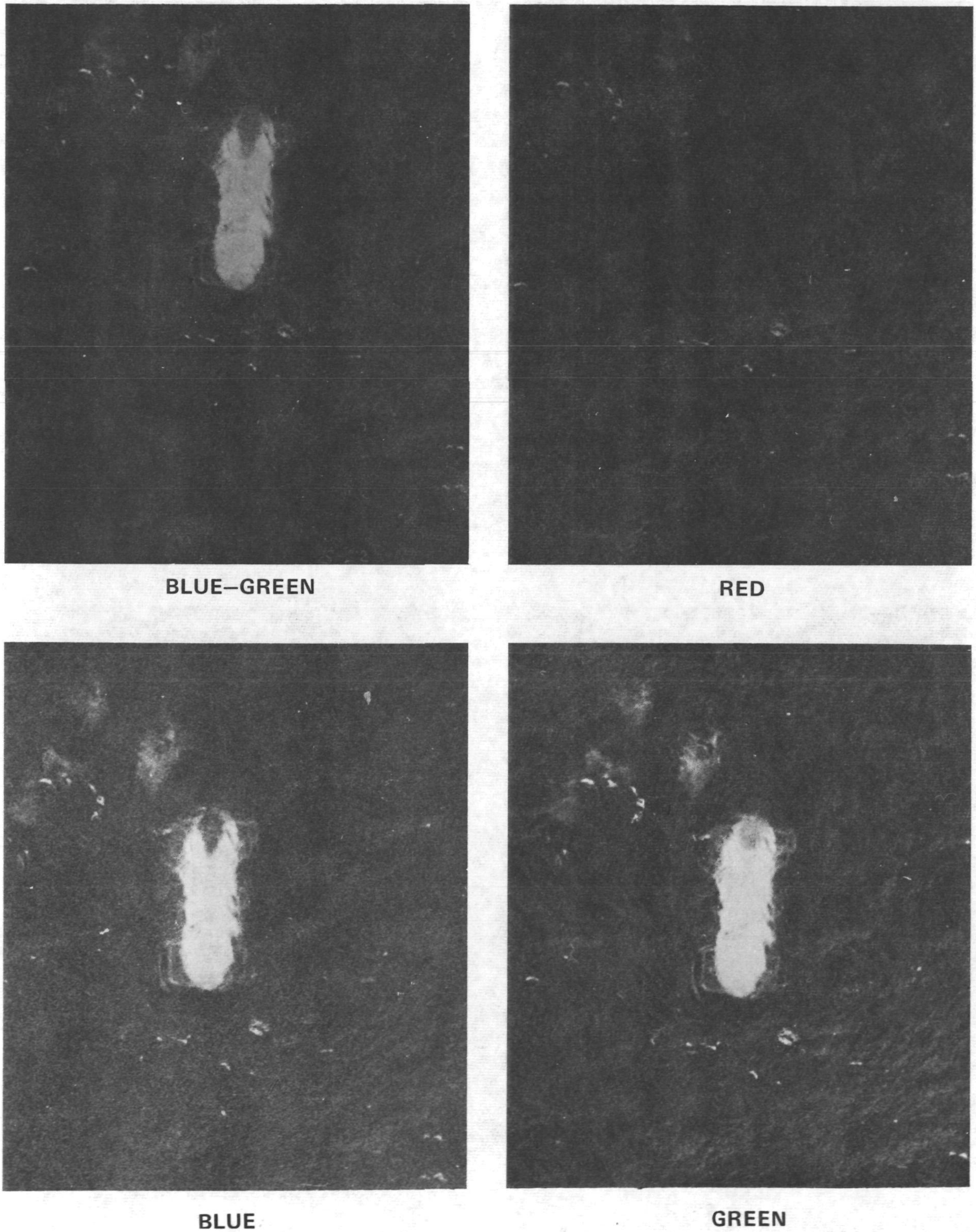

FIGURE 6. Multispectral photography of *Ben Franklin* at depth of 10 meters (from ref. 3).

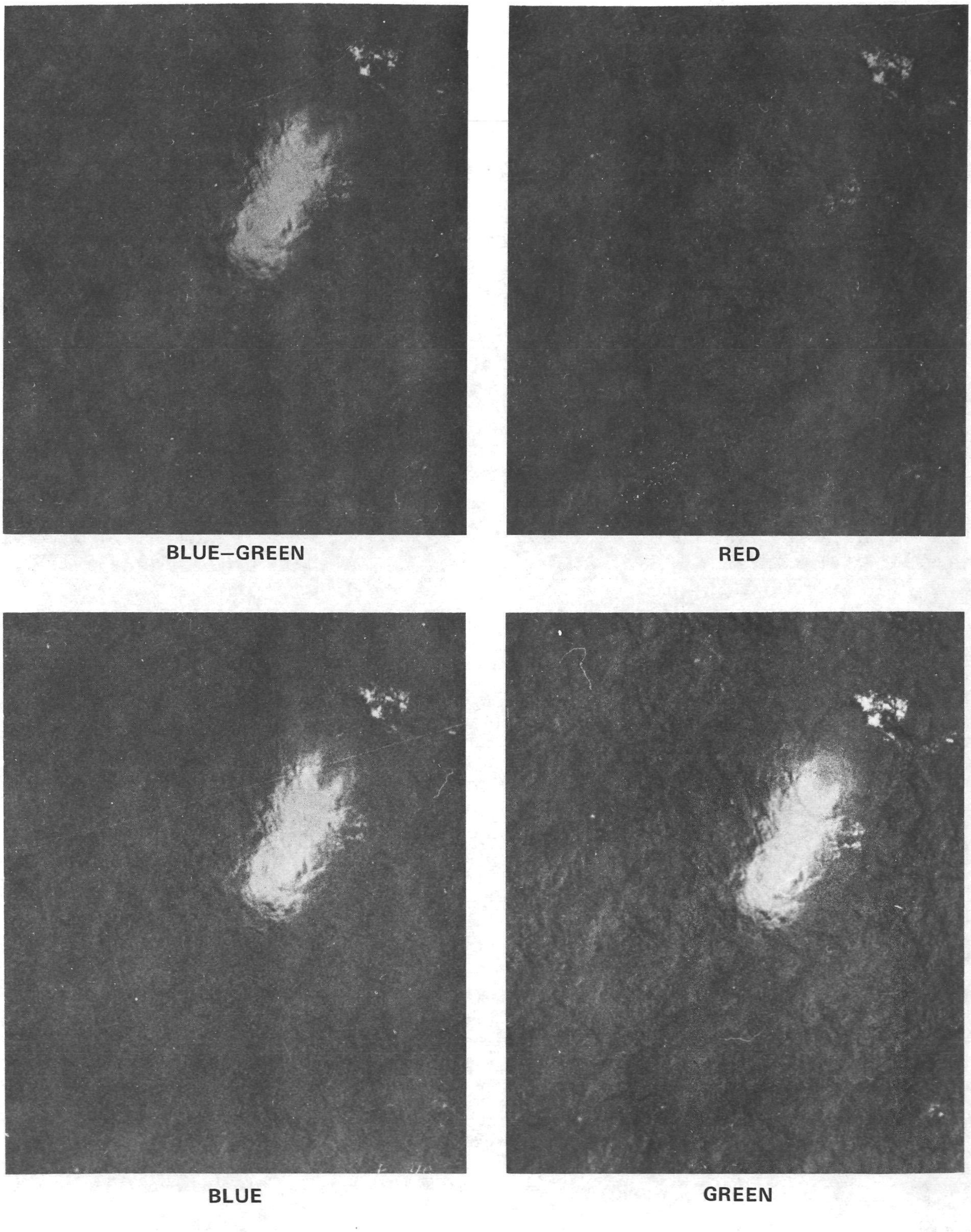

FIGURE 7. Multispectral photography of *Ben Franklin* at depth of 15 meters (from ref. 3).

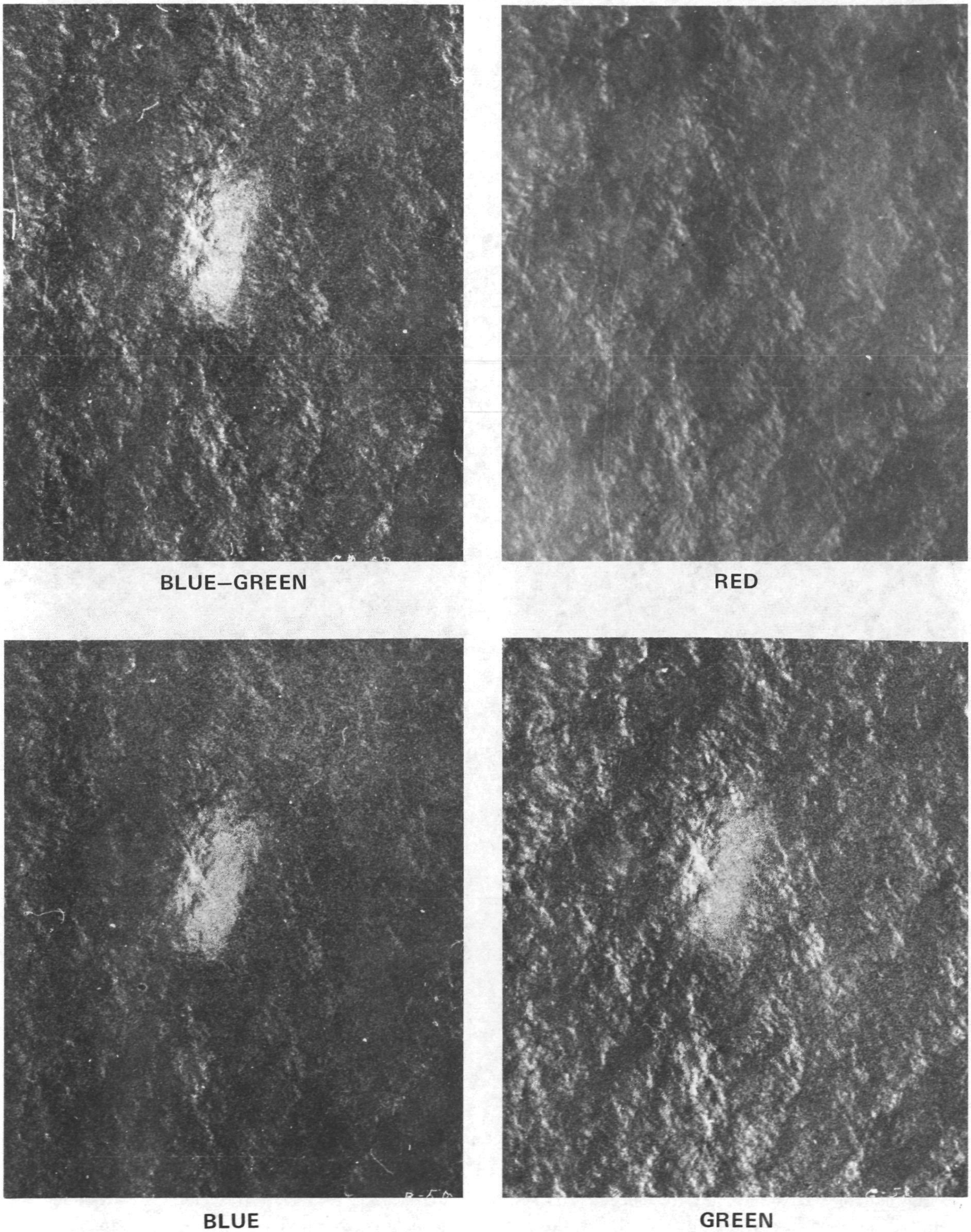

FIGURE 8. Multispectral photography of *Ben Franklin* at depth of 25 meters (from ref. 3).

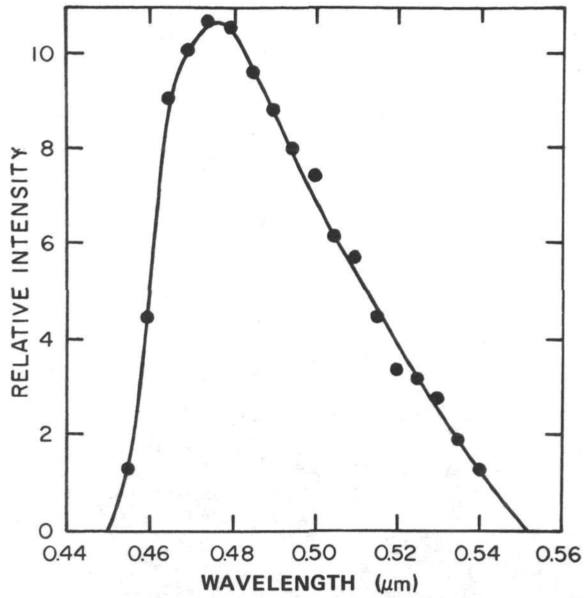

FIGURE 9. *In vivo* emission spectrum of luminescence produced on stimulation of *P. bahamense* (from ref. 7).

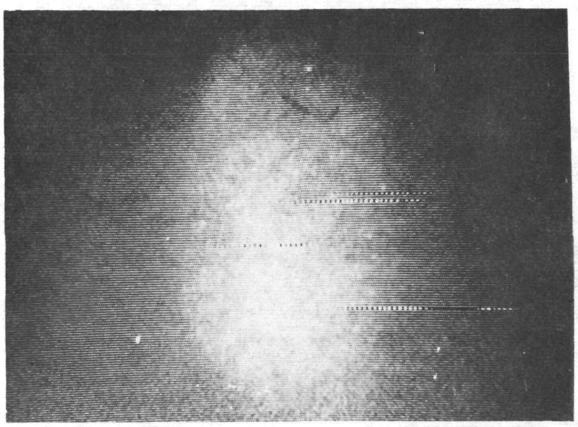

FIGURE 10. Low-light-level television image of bioluminescence induced by schooling fish, taken from altitude of approximately 1 km (Courtesy K. Drennan, Bureau of Commercial Fisheries, Pascagoula, Mississippi).

for studies of ocean temperature and color. These will be considered in the discussions which follow. It has historically been very difficult to study fish habits except at the location where the fish are being captured. The ecological drives which govern the movement of fish and their presence at a given place and time remain relatively unexplored. A satellite system capable of monitoring the ocean environment will allow behavioral studies of life in the sea, which are fundamental to understanding and preserving this worldwide resource.

SEA SURFACE TEMPERATURE

One of the first applications of remote sensors to ocean studies was the measurement of sea surface temperature. Aircraft infrared images such as figure 11 can reveal considerable fine detail about the

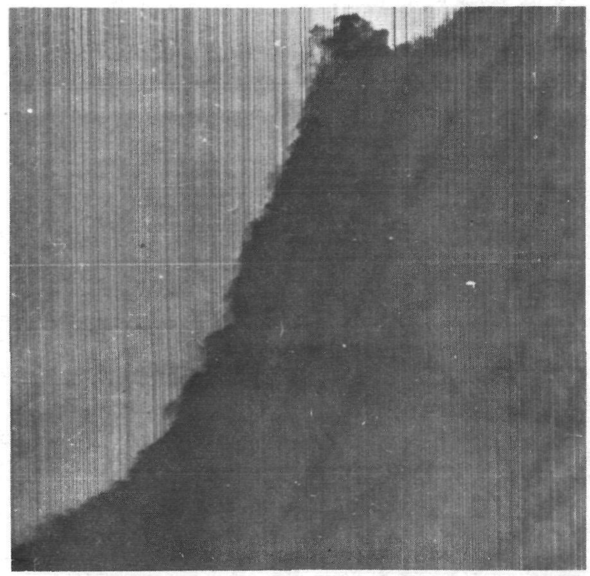

FIGURE 11. Aircraft infrared image of Gulf Stream with a radiation thermometer temperature profile.

ocean thermal structure that is not possible using ship measurements. The manner in which the surface temperature relates to the thermocline will require joint ship and remote platform measurements. A satellite thermal image, as shown in figure 12, does not show the fine detail of the aircraft image but does allow a synoptic view of sea surface temperature, including not only the warm Gulf Stream (darkest tone) and the near coastal currents, but also the intermediate water masses associated with the Western Atlantic shelf waters. This image, provided by the National Ocean and Atmospheric Administration, is from the Direct Readout Infrared (DRIR) system on ITOS, taken on October 19, 1970 (9 km spatial resolution, 1 °C thermal resolution, and 10.5 to 12.5 μm wavelength). While the DRIR system was designed primarily to map cloud cover at night (clouds appear cold or white in figure 12, as compared to the darker or warmer terrain and water features), it

can map relative sea surface temperatures when clouds are absent.

The conventional manner for displaying sea surface temperatures is with isothermal contours. The digital data from which the image of figure 12 was processed can also be used to generate isothermal maps of the surface. Figure 13 is an isothermal map made from the type of data used in figure 12, with a 2 °C temperature resolution. It has been shown in other experiments that the agreement between satellite and ship data is quite good when relative temperatures are compared.

Temperature can be related directly to certain fisheries. The herring fishery in the North Atlantic correlates very strongly with the gradient induced by the Arctic water mass normally found northeast of Iceland. But during 1967 the cold tongue of Arctic water moved further south and significantly altered the behavior of the herring. A survey by the Naval Oceanographic Office (NAVOCEANO) for the Icelandic government alerted Iceland to the continued anomalous behavior of the Arctic water mass.

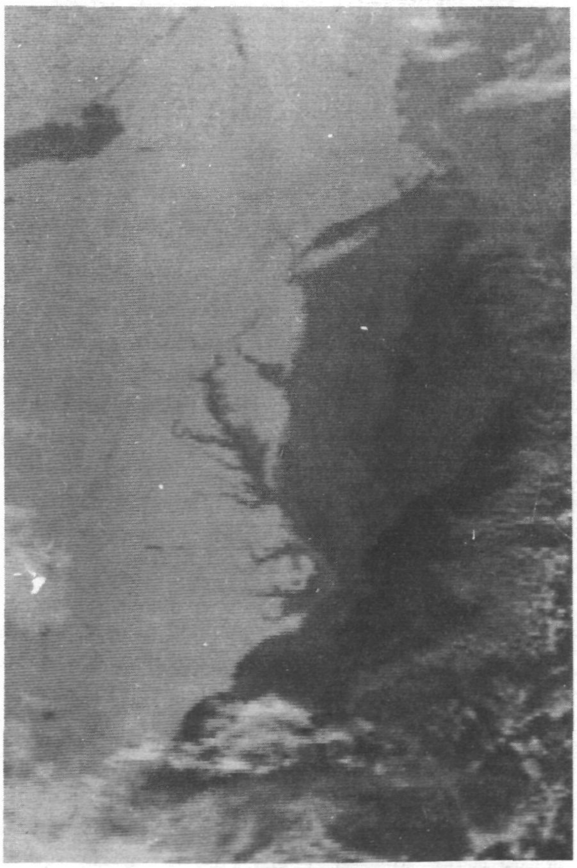

FIGURE 12. Direct readout infrared (DRIR) system image of western North Atlantic on the National Oceanic and Atmospheric Administration (NOAA) ITOS satellite, Oct. 19, 1970.

Because of the extended southerly reach of the Arctic tongue of water, many fishing vessels in Northern Iceland were icebound, when under more normal conditions these vessels could have left port more freely. Hence, sea surface temperature and the general sea-air interaction can play a strong role in many aspects of environmental monitoring which relate directly or indirectly to a given application, as illustrated here by fisheries.

SEA ICE

The Arctic and Antarctic are covered with ice, the former with a dynamic ice canopy over the ocean that reaches thicknesses on the order of 3 to 5 meters, and the latter with a relatively static ice crust covering the continent up to hundreds of meters thick. Ice in the dynamic North Pole region may move as much as 75 km in a day, whereas only in areas such as the Weddell Sea is there measurable ice movement in the area of the South Pole. All such ice movement affects transportation and the heat exchange which occurs in these regions.

Because of the dynamic nature of the North Pole area and the high occurrence of clouds and fog, microwave sensors are under development to penetrate the cloud cover. These sensors include both active and passive imagers on both aircraft and spacecraft. With satellites in polar orbit, a map of ice conditions in the Arctic can be generated on a daily basis and, by coordination with meteorological data, forecasts of ice conditions can be prepared and disseminated.

The same microwave sensors can also be used to observe the South Pole area, but the frequency of observation need not be as great in the Antarctic region. Many changes in the ice field in the Antarctic can be observed with existing television systems by monitoring relatively static conditions when no cloud cover impedes observation.

OCEAN COLOR ANALYSIS

The color of the ocean is determined primarily by nutrients, plankton, sediment load, pollutants, and often by bottom type and water depth. Phyto-

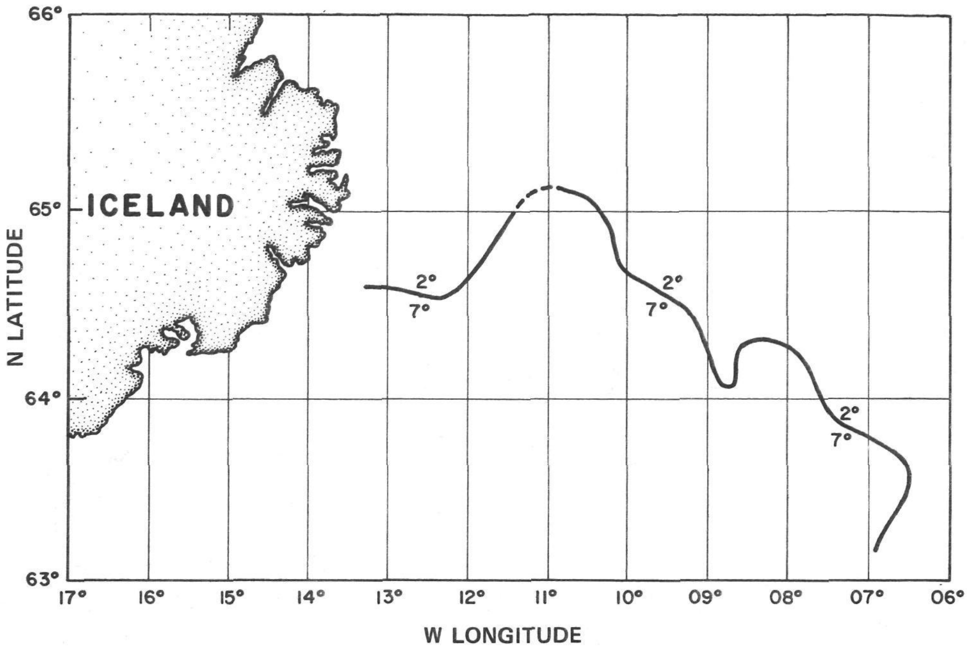

FIGURE 13. Location of a 5 °C surface temperature change aerially charted on 9 April 1968 by NAVOCEANO.

plankton abundance may be a basic indicator of the productive potential of a water mass. Living plants are capable of assimilating basic chemical nutrients from the sea through photosynthesis, for which chlorophyll is required. The ability to detect and quantitatively measure chlorophyll is believed to be a fundamental cornerstone in understanding the life cycle of the world's oceans. Such measurements on a global basis can eventually provide estimates of the productivity of the oceans and aid in preservation of "livestock" in the seas.

The development of remote sensors to study chlorophyll in the ocean takes on a different character from those developed for chlorophyll measurement from plant material growing over terrain. Chlorophyll has a very high reflectance in the near infrared region (approximately 0.7 to 0.8 μm). Hence, healthy chlorophyll shows a brilliant red in color infrared photography. The same technique when applied to chlorophyll in the ocean will detect only the surface chlorophyll (in the upper meter or so). The detection of kelp beds and surface algae is an application of such photography. Many ocean plants, however, grow at depths on the order of tens of meters, where red light energy is readily absorbed by water (see figures 2 and 3), so the red reflectance of chlorophyll cannot be observed from these depths.

Chlorophyll has a strong absorption band in the blue region, from about 0.42 to 0.46 μm. (There also appears to be a slight increase in the relative reflectance associated with chlorophyll in the green portion of the spectrum.) It is this absorption in the blue by chlorophyll, rather than reflectance in the red, that is being utilized to develop an ocean color system to measure ocean plant crops.

Figure 14 shows the manner in which the upwelling light as a percent of incident light changes as a function of chlorophyll concentration in the water and the wavelength of measurement. These data were acquired from an airborne spectrometer at about 325 meters altitude with a 0.005-μm spectral resolution, scanning from 0.40 to 0.65 μm in 4 seconds (ref. 8). The very low chlorophyll concentration is typical of very sterile water (like the Sargasso Sea) where chlorophyll is less than 0.1 mg/m^3; the low chlorophyll condition is typical of coastal slope water and is on the order of 0.3 mg/m^3; the high chlorophyll concentration is defined as up to about 3 mg/m^3. It can be seen that as chorophyll concentration increases the water will tend to be less blue and more green. It is anticipated

that an imaging ocean color spectrometer system will be capable of measuring chlorophyll on a quantitative basis with a logarithmic scale (i.e., <0.3, 0.3 to 0.6, 0.6 to 1.2, 1.2 to 2.4 mg/m^3, etc.) over the interval from about 0.3 to perhaps 20 mg/m^3. This range is the region of most interest for typical chlorophyll measurements.

There are other factors which must be considered and assessed in measuring ocean color. These are the atmosphere, Sun glitter, and foam. The effects of the atmosphere, especially in the blue region, must be determined and extracted from the spectrometer signature. The amount of data collected thus far is too meager to allow any specific statements other than it does appear that atmospheric effects can be dealt with for relatively clear sky conditions.

Sun glitter occurs as a result of direct reflection of sunlight from the ocean surface. The closer to midday a visible-region sensor is operated, the more likely a glitter pattern will occur in the field of view of the instrument, thus obliterating information about the water column itself. On the other hand, the closer to midday one operates a visible-region sensor the more likely that local haze conditions will have dissipated, providing a more favorable environment for observation. It might appear then that the most desirable time for observation would be in the afternoon to avoid both haze and glitter. However, in many regions convective activity may produce an abundance of cumulus clouds and possible thunderstorm buildup by the afternoon, presenting an additional hindrance to observation.

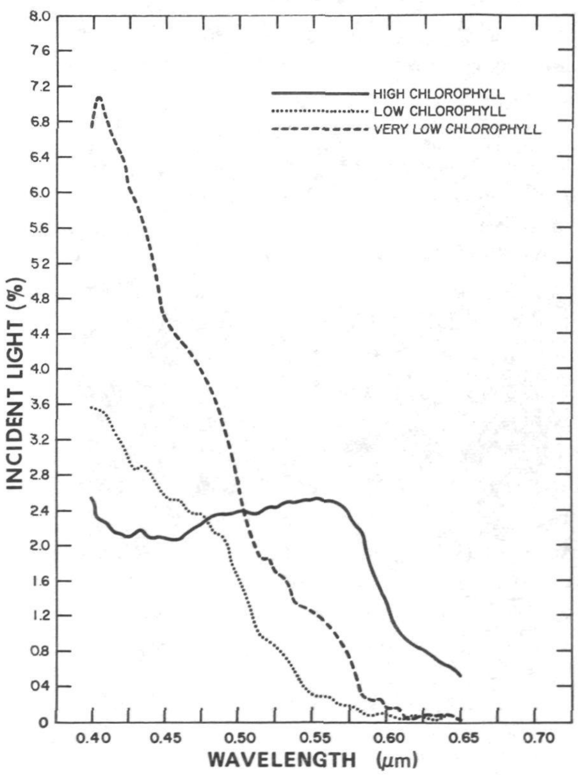

FIGURE 14. Relative energy reflected from ocean water as a function of wavelength and presence of chlorophyll (from ref. 8).

For ocean color analyses related to coastal processes, which will be discussed in a following section, the Sun glitter problem must also be related to the tidal cycle in a given region. Observations need to be made in most cases during both high and low tide conditions. When tidal cycles are related to the Sun glitter problem, there may well be only two or three days a month when effective observations can be made.

It is important also to consider that glitter pattern data are of great value in delineating surface features, particularly those of pollution. Indeed, when ocean phenomena related to surface effects are required, the use of glitter pattern analysis should be included.

Analyses of ocean color are best made with calm sea conditions, again to avoid glitter that might be reflected from waves, but also to minimize the amount of foam that might be present. Foam is generated by both breaking waves and wind and can be dealt with on a statistical basis if necessary by averaging observations over time. However, individual or short samples of spectrometer-type data should be avoided. The curves in figure 14, while acquired with a 4-second scanning spectrometer, are composed of many such samples (totaling one to two minutes) which have been averaged in order to eliminate major surface differences.

SHOAL AND COASTAL MAPPING

Coastal mapping uses the same techniques as terrestrial mapping, the major differences being that in many locations coastal region land/water interfaces change much more rapidly. Tidal cycles can cause day-to-day changes, but basic coastlines are charted primarily for the high-water condition. This condition is the one usually shown on charts.

Horizontal dimensions of coastlines in some areas may change permanently by magnitudes on the order of hundreds of meters per year. This phenomenon often leads to several forms of land dispute if such changes are not properly recorded on coastal maps or brought to the attention of appropriate land authorities.

The bathymetry of coastlines may change on a permanent as well as a seasonal basis, due to sand shifting with the seasonal environment. In many cases the shifting is favorable to reducing storm damage. Such seasonal changes are measured with *in situ* techniques. In relatively shallow water, to a depth of 20 to 30 meters, remote sensors of several types may be used for such measurements. The techniques include the use of visible-region photographs or images, as well as laser systems which directly measure the depth from aircraft.

Shoals are shallow-water features which endanger vessels because they typically remain submerged below the sea surface. Often they are associated with the shallow waters along the coastline, but they also occur as anomalous features in otherwise deep water. The methods proposed to detect and chart the 3000 or more "doubtful" shoals* are the same as those for bathymetric surveys of coastlines using remote sensing techniques.

Because only the density slicing technique for photography has had appreciable use in measuring relative depth, it will be discussed briefly here. The wave refraction technique is dependent on proper environmental conditions (ref. 9), and the laser approach is now under development, with the result that neither of these have been used to the extent of density slicing.

Photography or imagery in the blue or green portion of the spectrum is used in determining relative depth in a given location. Emulsion levels of the same density may be selected most simply with a densitometer scan of film (or by computer selection of digital imagery data) along any portion of the film (ref. 10). This density slice correlates quite well with depth if water contaminants and bottom type are uniform. More sophisticated density slicing can be accomplished photographically wherein whole layers of a given exposure density are sliced from the photograph. The result is a "slice" which generates relative depth contours. Such slices are frequently given a false color and a composite of the slices reformatted, allowing the relative depth contours to be viewed in the context of the original image (ref. 11).

The analysis of photography by this density slicing technique is made difficult when there are varying sediment loads in the water or when the bottom changes appreciably over the region of interest. Nevertheless, the technique has been used to analyze space data and is an excellent technique for monitoring regions where depths are subject to change.

COASTAL MARINE PROCESSES

The general study area of coastal marine processes includes: the physical interaction between ocean, coastal, and river-induced current systems; the prevailing environmental conditions; the rotation of the Earth about its axis; the gravitational effects of the Moon and Sun; and man-made effects. In addition, the study of coastal marine processes may also be extended to include the relationship between the physical environment and the biological environment (particularly in regions of coastal upwelling) and the influence of man on this relationship.

No special remote sensors are required for studies of coastal marine processes, since it appears that the instruments developed for terrain and other ocean applications are appropriate to this study. Indeed, the instruments developed and to be deployed on the first Earth Resources Technology Satellite (ERTS-A) can be used for these types of studies.

Because of the immediate application of ERTS-A to the study of coastal marine processes, an International Workshop paper entitled "Oceanographic Interpretation of Apollo Photographs" has been prepared by Mr. Robert Mairs (volume II of these proceedings). Some of the types of analysis necessary for coastal marine process studies and the manner in which ERTS-A data may be used to assist in these studies are described in this paper.

SYNOPTIC OCEANOGRAPHY

Remote sensors on both aircraft and satellites have shown that the ocean is a very dynamic environment. In order to quantify the remotely sensed data from these platforms, remote sensors in labora-

* These are shallow-water features which have been reported by ship soundings but have not been confirmed by a precise fix on hydrographic charts.

tories, towers, and ships are being employed to provide the link between conventional oceanographic *in situ* techniques and those using air- and spaceborne platforms. These surface remote sensors range from the electron microscope to the radio telescope and from complex spectrometers to relatively simple cameras. Given the proper quantitative data for interpreting aircraft and spacecraft data, a significant measure of the nature of the world's oceans potentially can be assessed.

Is such an assessment necessary, and if so, is it appropriate to do so using remote sensors? The answer to the first portion of the question is clearly affirmative because remote sensors have already shown that many areas of the ocean are not the vast wasteland of sterile water they have historically been believed to be. The synoptic view of the oceans provided by remote sensors allows what seem to be very slight changes at a specific point and time to be placed in the context of similar changes in other regions at the same time. The second portion of the question cannot be answered fairly until further research is conducted from surface, aircraft, and satellite platforms. Indeed, an ocean monitoring system will in all likelihood contain elements of *in situ* sensors at the surface and subsurface, aircraft instrumentation to measure both ocean and atmospheric conditions, and satellites to provide the overview of ocean behavior—a relatively new field of exploration called synoptic oceanography.

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Environmental Monitoring By Remote Sensing From Air and Space

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People around the world have today become newly aware of the environment, not only as the provider of resources for economic development, but as the basis of life itself, within which man and his children must live for centuries to come, if they are to live at all. There is rising concern all over the world both for the effect of the natural environment on man and his activities and for the rate at which the environment is being degraded with the growth of technology and the progress of economic development. There is genuine fear that environmental quality may not only decline sufficiently to make life unpleasant, but even to the extent that human life may become impossible on the terrestrial globe. In the meantime, growing population densities and increased value of structures and property mean that every new hurricane, earthquake, or other natural disaster potentially takes an increasing toll of human life and economic resources. Thus, as a matter of self preservation, we must become concerned with the environment in all its aspects. We must learn to understand the natural environment and its processes and the threats it may pose, as well as the means by which man's activities interact with the environment and tend to change it.

An important first step toward achieving these objectives is to describe the total environment in sufficient detail to permit modeling of its processes and measuring its changes on a worldwide basis. This process of observing the environment and measuring its changes is called environmental monitoring. Environmental monitoring obviously is not a new activity. For well over a hundred years regular observations of atmospheric variables have been made over wide geographic areas from surface stations, and later from balloons and other platforms. To a more limited degree, oceanic parameters have also been measured for many years. What is comparatively new is the need to measure and observe all elements of the environment over the entire globe and to acquire such data in a relatively short period of time. It is in this context that remote sensing from air and space is beginning to play such an important role in environmental monitoring, and it is this application of remote sensing which I wish to discuss with you today.

We monitor the environment for a number of different purposes. To an extent, the purpose determines how quickly we need the data and over how large an area. Of highest immediate priority in terms of protecting human life is perhaps the direct detection of imminent environmental hazards and the provision of timely warning to threatened areas. Such hazards include hurricanes, tornadoes, and other severe storms; tsunamis (seismic sea waves); floods, landslides, and unusually heavy snowfall; and other events similar in nature where timely warnings could permit taking action to save lives and protect property.

A second critical application of environmental monitoring is to the prediction of short-term environmental change: forecasting the weather, the state of the sea, the probability of earthquakes, or the occurrence of a solar flare which might produce radiation levels in the upper atmosphere hazardous to high-flying aircraft. Another type of environ-

mental change of growing importance in the preservation of environmental quality is the long-range climatic change which may be caused inadvertently by man's activities. An application to this problem that is becoming more vital every day is the monitoring of air and water pollution, both regionally and globally. Regional aspects of pollution monitoring will be discussed in more detail in the following paper.

Finally, environmental monitoring is directly related to the identification and management of the resources of the atmosphere, the oceans, lakes and rivers, and the solid Earth. These applications will be discussed in many papers presented at this workshop. The emphasis here is on applications of environmental monitoring techniques to warnings of environmental behavior and measurements of environmental quality on a global scale.

Much progress has already been made. To some extent, environmental monitoring from space is already being done operationally by the United States, using the environmental satellites of the National Oceanic and Atmospheric Administration (NOAA), and to a lesser extent by other nations. The polar-orbiting Improved Tiros Operational Satellites (ITOS) now observe the entire Earth twice a day, taking television cloud pictures and radiometric images. Beginning in 1972, these satellites will obtain daily readings globally of the vertical distribution of atmospheric temperature and humidity. Imaging resolution will be improved to approximately 1 kilometer directly below the satellites. The Geostationary Operational Environmental Satellite (GOES) system, also scheduled for operational checkout in 1972, is capable of continuous observation of the region over which it is positioned; it will produce multispectral (visual and infrared) images of most of the Western Hemisphere night and day at half-hourly intervals. Both systems will carry sensors to monitor emissions from the Sun.

With regard to observation of the solid Earth, satellites usable for obtaining accurate geodetic location of points on the surface of the Earth, even at intercontinental distances, have been flying since the launch of Echo I in 1961. While no satellites have been launched specifically to monitor the world's oceans, a start has been made using data available from meteorological satellites.

Aircraft also have been used for environmental monitoring by the United States and other countries. For example, aircraft of the United States Navy, Air Force, and the NOAA have been used for many years in locating and tracking tropical storms and monitoring other meteorological phenomena. Aircraft photography also has been used to determine snow cover over portions of the United States to assist in predictions of runoff and flood potential. Scientists of the NASA Earth Resources Survey Aircraft Program have been investigating the use of remote sensors for a variety of environmental applications, most of which will be described at this workshop. The first Earth Resources Technology Satellite (ERTS) is scheduled for flight in early 1973, as is the Earth Resources Experimental Package (EREP) on the manned Skylab satellite. Both are expected to increase our understanding of the extent to which remote sensing from space can contribute to environmental monitoring.

While I have been emphasizing the use of spacecraft and aircraft for environmental monitoring, I do not wish to minimize the importance of surface and other *in situ* sensors. Some data can be collected only *in situ*. Even where remote sensing may be the predominant mode of data acquisition, there is an axiom that holds true for all applications: Remote sensing data are useless in the absence of adequate ground truth or other *in situ* information. For example, satellite cloud photographs cannot be used to make weather forecasts unless the relationships between cloud forms and weather phenomena have been established previously. In keeping with the theme of this workshop, however, the emphasis in this paper is principally on remote sensing by satellite and aircraft as an element of the total spectrum of data acquisition required for environmental monitoring.

I would like now to review some accomplishments in environmental monitoring which have been achieved using data acquired by remote sensing from air and space, together with data from other sources.

Satellite data have powerful applications in the forecasting and warning of our most dangerous weather phenomena, the deadly and destructive hurricanes and tornadoes. Since inauguration of the operational satellite service in the United States, probably no tropical storm has gone undetected anywhere in the worldwide tropical oceans. Dis-

covery is invariably by satellite. For example, in the virtual absence of other weather reports south and east of Hawaii in the Central Pacific, many tropical storms would go undetected without satellite surveillance, and a violent storm could strike the islands without warning as has happened in the past. Figure 1 shows an example. In late August 1970, Hurricanes Maggie and Lorraine were east of Hawaii and were thought to be weakening. But in the satellite picture for August 25 the cloud structure of Maggie, the nearer storm, showed she was still intense. On the basis of this information, the forecaster called for much heavier precipitation than he otherwise would have. The next day Maggie brushed by the island of Hawaii and produced very heavy rainfall. Lorraine, on the other hand, was correctly forecast from the satellite pictures to be no threat to the islands.

Figure 2 is a photograph of an approaching tornado—the most dangerous of all storms. We do not yet understand how to predict the occurrence of tornadoes with any d‿gree of certainty. On the other hand, the nearly continuous cloud photographs available from geosynchronous satellites, such as the sequence from ATS III shown in figure 3, permit quick identification of regions in which such severe storms might occur. Ground-based radar, another form of remote sensing, because of its current availability to the forecaster, is of special value when tornadoes are forming. Figure 4 shows a sequence of radar photographs made in the vicinity of Lubbock on the same day as the satellite photos of figure 3.

While there are a number of applications of remote sensing techniques to environmental threats and disasters, of which these two examples are representative, there are other types of disasters (earthquakes, for example) for which we have not yet developed warning techniques. It is hoped that, as we gain experience with remote sensing, these techniques will be developed.

In the area of short-term prediction of environmental events, there has been significant application of environmental monitoring by remote sensing techniques. Figure 5 is a computer-prepared mosaic of the Northern Hemisphere on September 13, 1969, which shows the distribution of clouds for the entire region. This type of mosaic is now used routinely

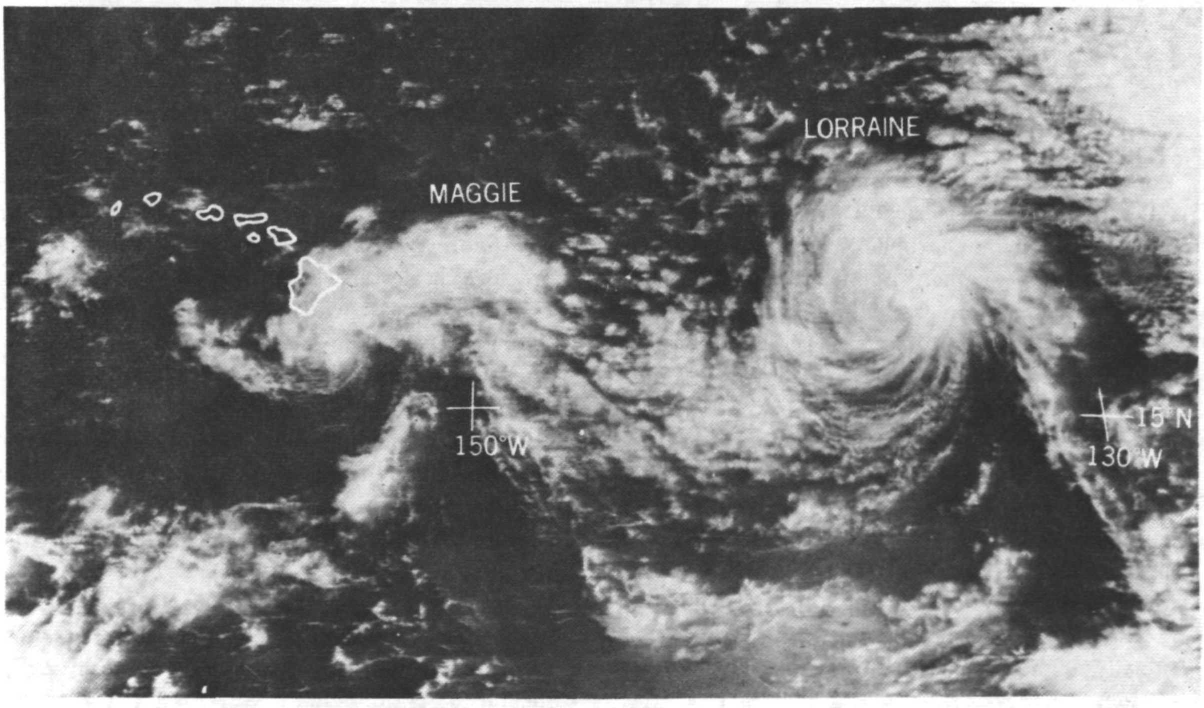

FIGURE 1. Hurricanes Maggie and Lorraine east of Hawaii, August 25, 1970.

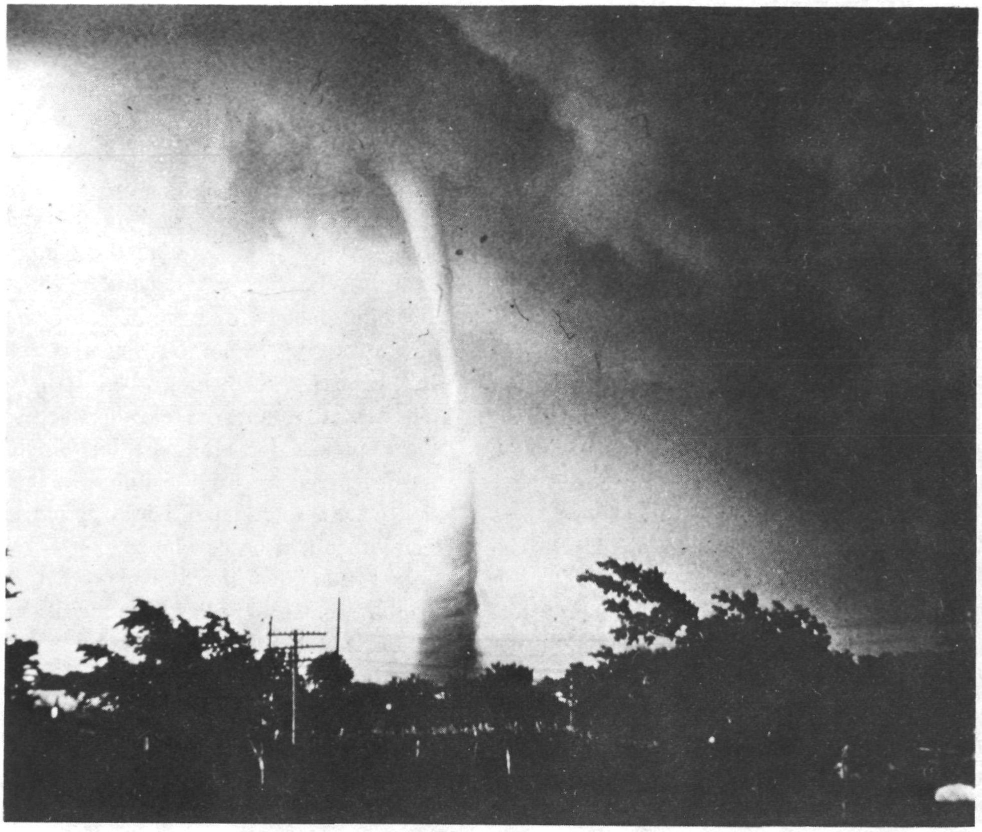

FIGURE 2. The most dangerous and unpredictable of all storms, a tornado approaches with devastating speed.

by the National Meteorological Center at Suitland, Maryland in the preparation of Northern Hemisphere and North American weather analyses.

While cloud photographs are of great value in portraying the weather situation, the meteorologist cannot prepare a forecast without quantitative data on the state of the atmosphere. A beginning has been made in obtaining quantitative data from satellite-borne remote sensors.

Figure 6 compares remote sensing data taken from the satellite infrared spectrometer (SIRS) flown on Nimbus III with conventional sounding data taken from balloonborne radiosondes the same day. SIRS uses infrared radiance at a variety of wavelengths to determine the vertical temperature profile of the atmosphere. Agreement with conventionally obtained observation is excellent at this station.

Although such infrared observations from a satellite can be made only above the cloudtop level, except in cloud-free areas, the data permit the construction of a number of useful products. For example, figure 6 also shows a 300-millibar constant-pressure chart prepared entirely from satellite soundings as compared with the chart for the same time period prepared from conventional sounding data. Such charts are used in the preparation of weather forecasts.

Knowledge of the global sea surface temperature is an essential type of data for improving long-range weather forecasts because it contributes to knowledge of the total energy balance of the ocean-atmosphere system. Figure 7 represents the temperature distribution in the Pacific Ocean as determined by satellite infrared sensors on Nimbus II. This type of information is currently available on an experimental basis in cloud-free areas over the entire globe.

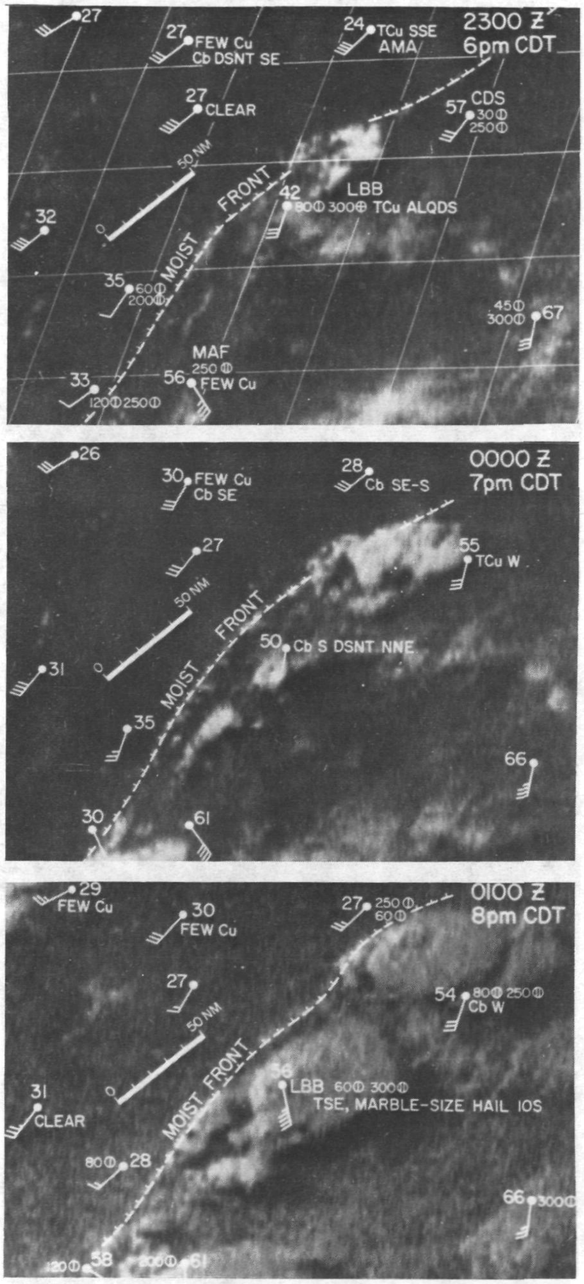

FIGURE 3. Series of photographs from ATS III, taken at 1-hour intervals on May 11, 1970, shows tornado activity in the vicinity of Lubbock, Texas.

Knowledge of the presence of ice and snow over land and sea is important both for weather forecasting and for predicting the amount of water which will be available in rivers and lakes following runoff. Such information is also of importance in predicting hazardous floods. Figure 8 is a satellite photographic mosaic for March 10, 1970, showing clouds usually visible in a satellite photograph. By a special process, a composite mosaic (figure 9) showing only the minimum brightness that appeared over an area during 5 successive days is produced. In this composite all but the most persistent cloudiness has been removed, and the remaining bright areas represent ice and snow. This type of product is now being prepared regularly by the National Environmental Satellite Service.

Interest in environmental prediction extends to regions other than the atmosphere and oceans. For example, sunspots, solar flares, and other types of disturbances may affect communications, space and aircraft operations, and even electric power networks on the Earth's surface, so it is necessary to predict such events and their effects on other regions of the environment as accurately as possible. The Space Disturbance Forecast Center of the NOAA makes such predictions, making extensive use of satellite data. Figure 10 shows schematically how this function is performed. At present, the principal sources of satellite data to the center are the NASA ATS satellites and the NOAA satellites. Beginning in early 1973, the GOES satellites will become an important source of data, and other sources will be added in future years.

We come now to an application area of very great importance, even though the time dependence of the data is less critical. The application I refer to is that of detecting climatic change, whether attributable to natural causes or to changes connected with weather as we normally think of it, but also to changes or trends in any aspect of environmental quality. This is currently an area of very great concern in the United States. In response to this concern, NOAA has recently prepared a geophysical monitoring plan for climatic change. Here we are concerned, for example, with trends in average temperatures and rainfall, the amount of carbon dioxide in the atmosphere, pollution of the atmosphere by harmful particulate and gaseous matter, water pollution, and land use.

Very accurate point observations are made at key climatic reference stations, such as the one at the top of Mauna Loa on the island of Hawaii (figure 11). Such stations, located in regions generally free from local pollution sources, provide reference

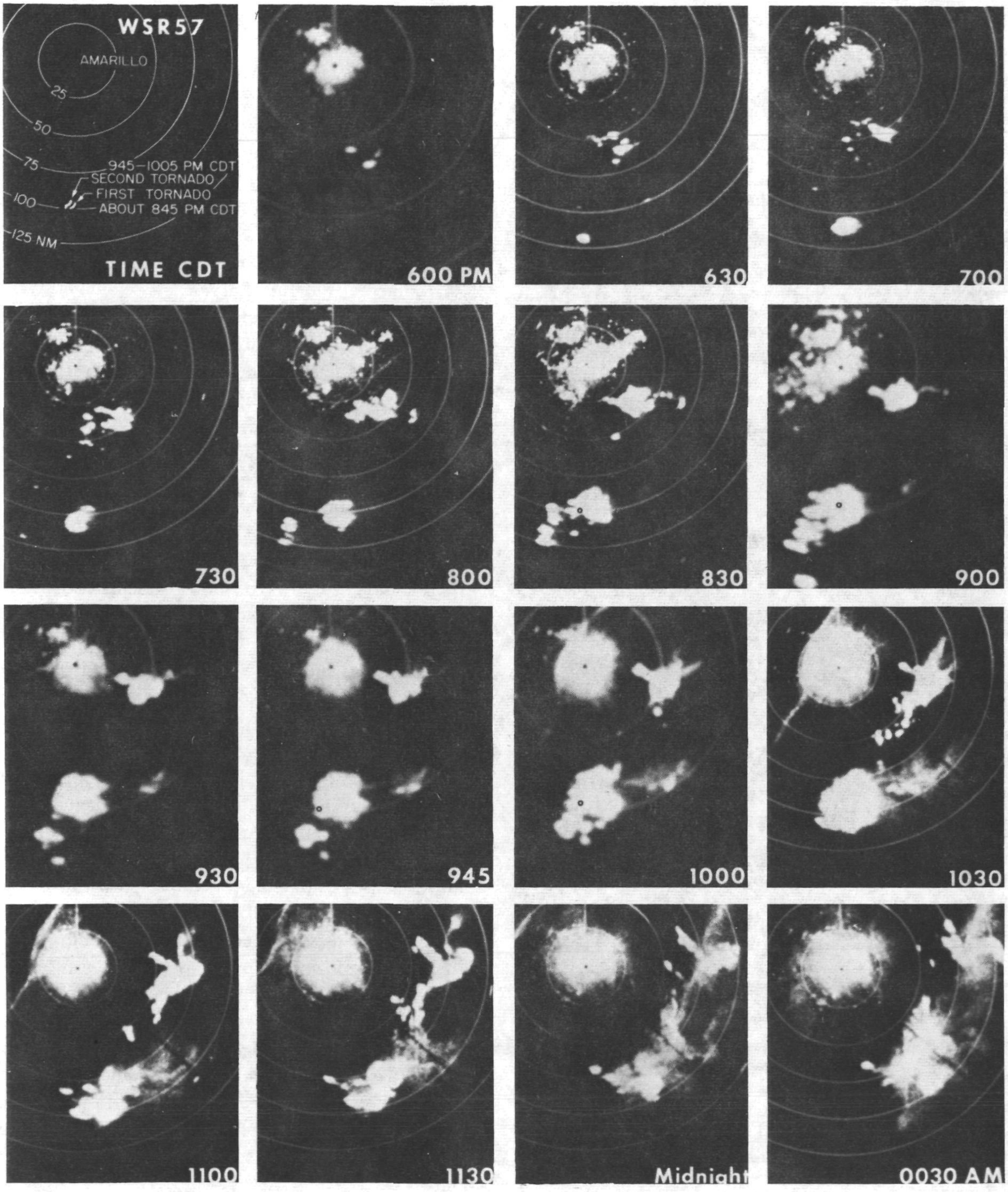

FIGURE 4. Series of ground-based radar photos shows same tornado activity near Lubbock on May 11, 1970.

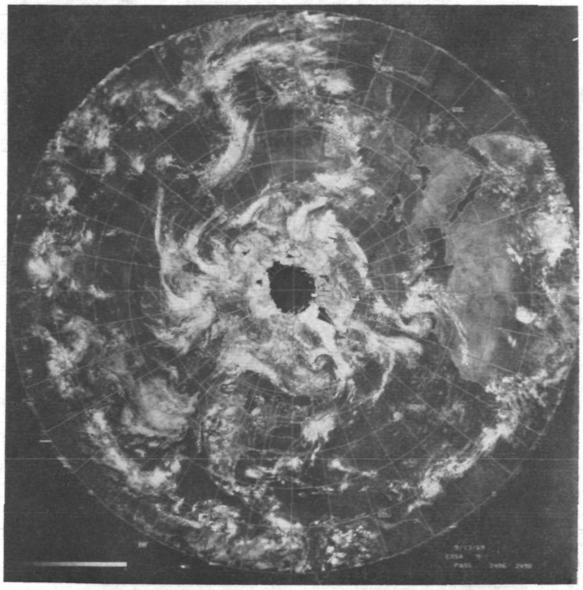

FIGURE 5. Cloud distribution over entire Northern Hemisphere is shown in this computer-prepared photomosaic.

data to which other observations may be related. Byrd Station in Antarctica is another key reference station.

Since a large percentage of the world's fresh water is stored in the form of snow and ice on the Antarctic Continent, and since approximately 65 percent of the net blackbody radiation needed to maintain the Earth's equilibrium temperature is emitted from that continent, temperature and precipitation trends in this region are critical to world climate. To further this knowledge, deep holes have been drilled in the glacial ice at Byrd Station and at Camp Century in Greenland. Examination of the various layers of ice has revealed the climatic history of the Earth for approximately the past 40 000 years, providing a reference for present trends. Figure 12 is a cloud-free photograph of the Antarctic Continent made using the composite minimum brightness technique.

The significant value of satellite remote sensing observations is that they provide a means for relatively reliable interpolation between surface climatic reference stations. For example, figure 13 represents a 30-day brightness average from mid-July to mid-August 1969 for the Northern Hemisphere; this is an indication of the mean cloud cover and precipitation for the month. Figure 14 is a 90-day average during the winter of 1970–71.

Turning now to another part of the environment, the coastal zones of the continents are an important source of both mineral and biological resources. But they are very susceptible both to pollution and to misuse by man. The so-called wetlands or marshy areas in the vicinity of the coast are very important ecologically. Figure 15 shows a black-and-white print of a false-color infrared photograph (top) and a print of the infrared channel only (bottom) of the coastal area of the State of Georgia in the southeast part of the United States. This type of photography permits clear identification of the wetlands, as can be seen in the upper photograph. Repetitive coverage permits monitoring the quality of this portion of the environment and rapid detection of any significant change.

These examples indicate what has been done and can be done with current technology for environmental monitoring. We have only begun to use remote sensing for this purpose; most applications are still in the planning stage. Because of the importance to all of us of the future of the global environment, I would like now to talk a bit about the future and what it may bring in the way of tools for environmental monitoring. I would also like to speculate a bit about ways in which we may work together in the future to insure a better environment for all mankind.

I have mentioned the value of satellite remote sensing for interpolation between surface observations. This application should increase in the future as we find means to measure more variables by remote sensing. For example, the ability to obtain global temperature and humidity soundings daily, even from remote areas where there are no observers present, will greatly contribute to our knowledge of world climatology.

The acquisition and storing of data, while of great value in itself, is not itself sufficient to solve all environmental problems. A very high-priority objective must be to develop a capability to model the total environment and its interactions. Only with such models can we determine the consequences of man's activities. The ability to observe and collect data continuously over the entire globe will inevitably make a major contribution to meeting this objective.

Already we are modeling the Earth's atmosphere, at least to some extent; these models are the

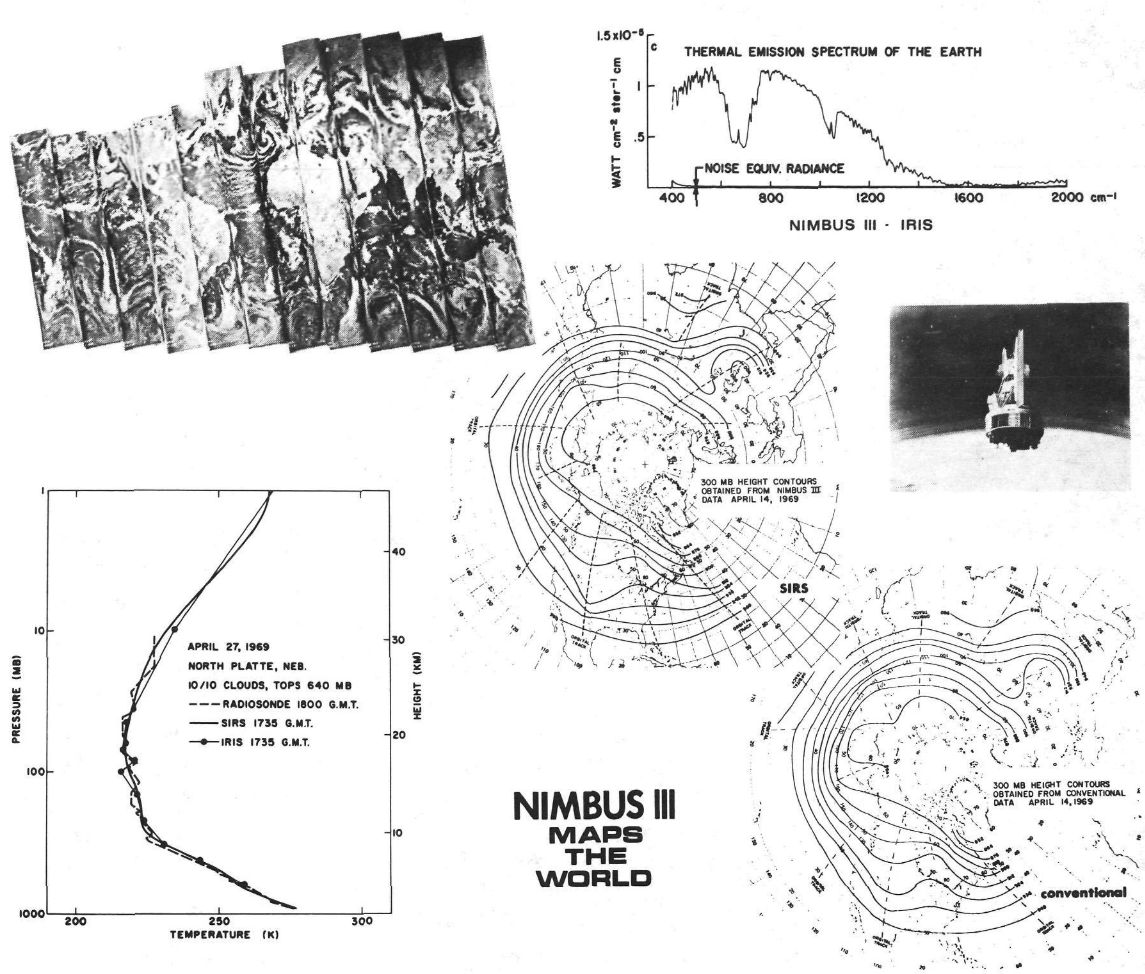

FIGURE 6. Satellite infrared spectrometer (SIRS) data compares closely with conventional sounding data.

basis of long-range weather forecasts. We must now extend this concept to include the total spectrum of the environment, from the input of solar energy through the dynamic processes of the upper and lower atmosphere to interactions with the turbulent oceans and the solid Earth beneath. Our models must be sufficiently accurate to predict the long-term effects of collective human actions such as pollution, as well as individual actions such as weather modification experiments. Within the next 10 years or so, we should have the capability to observe virtually the entire physical environment and its dynamic changes. Continuous global observations will enable us to complete the modeling necessary for accurate prediction.

Other regional and global measurements will be needed to monitor environmental quality and prevent its degradation. We will need to identify certain key indices of quality and attempt to relate these indices to parameters which may be observed from air and space. I should like now to speculate as to what some of these indices might be and how data for their monitoring might be obtained.

What are the significant indices of environmental quality? In the absence of adequate environmental models, this question is difficult to answer. We are not sure we understand all of the parameters or the functional relationships between these parameters and environmental quality. Nonetheless, it may be useful to suggest a list as a starting point for discussion.

First of all, we do not understand by what means

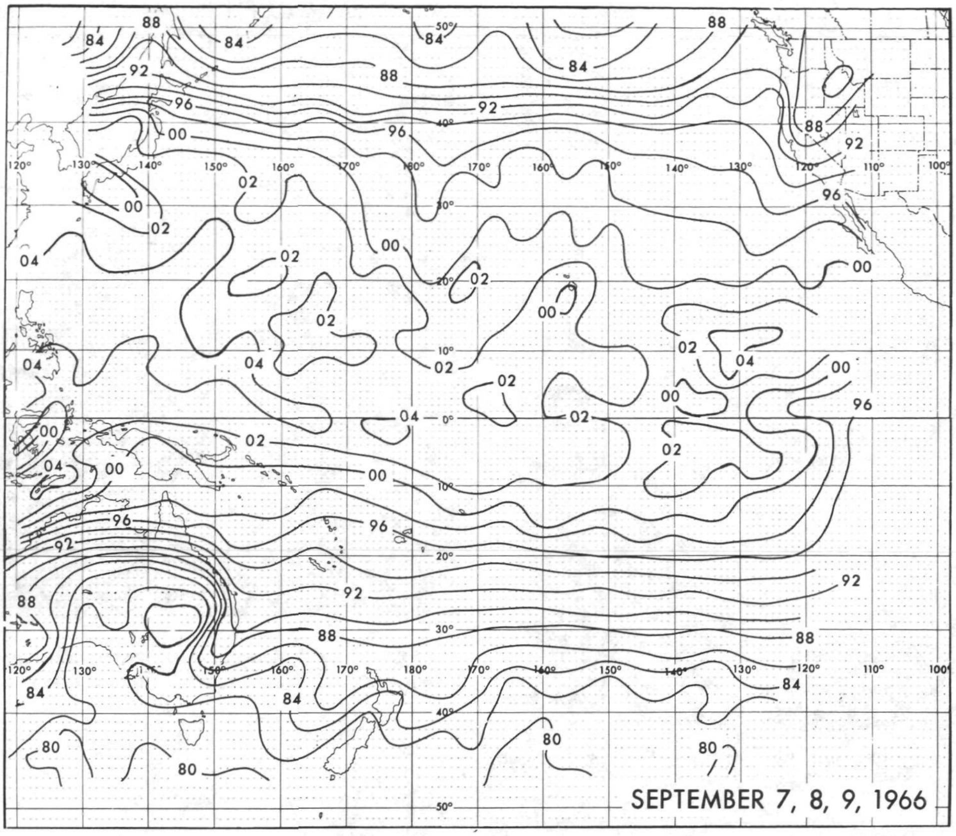

FIGURE 7. Pacific Ocean temperature distribution prepared from Nimbus 2 IR sensor data.

events on the Sun affect the environment here on Earth. At the same time, it would be foolish to assume at this point that solar events do not affect environmental events, at least in the upper atmosphere. We are already collecting data, much of it by satellite, concerning sunspots, solar flares, solar particle emissions, and other significant events. In each case, indices of activity can be established. Similarly, we measure electron and ion densities in the upper atmosphere and fluctuations in the Earth's magnetic field.

In the lower atmosphere, there are undoubtedly a number of parameters related to environmental quality. These parameters in general have significance both regionally and globally and hence must be indexed as a function of time, place, and altitude. Such parameters include the vertical distribution of atmospheric temperature, humidity, density, cloud cover, and precipitation, all of which are conventional climatic parameters. Surface temperature is another important parameter which must be indexed, and the mean temperature of the Earth is almost certainly an environmental quality factor of great importance.

With particular regard to air pollution, several additional parameters might be measured. These include, in addition to the climatic variables already identified, such factors as turbidity, particulate and gaseous contaminants, and the height of the mixing layer. As an example of how an index might be derived for one of these parameters by remote sensing, one might install high-intensity monochromatic light sources at key cities around the world for viewing by multispectral sensors. Whenever cloud-free conditions exist, both absorption and frequency shift could be observed, and net particulate contamination as well as particle size distribution might be deduced. Active laser systems carried on a satellite might make possible the measurement by Raman scattering of gaseous contaminants such as NO and NO_2 for the same regions. With this type of data available, it should be possible to develop

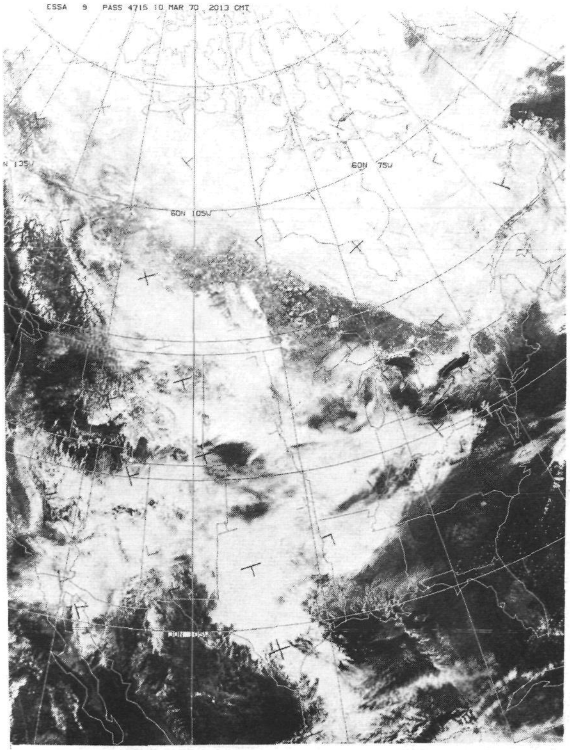

FIGURE 8. Satellite photomosaic showing entire visible cloud cover.

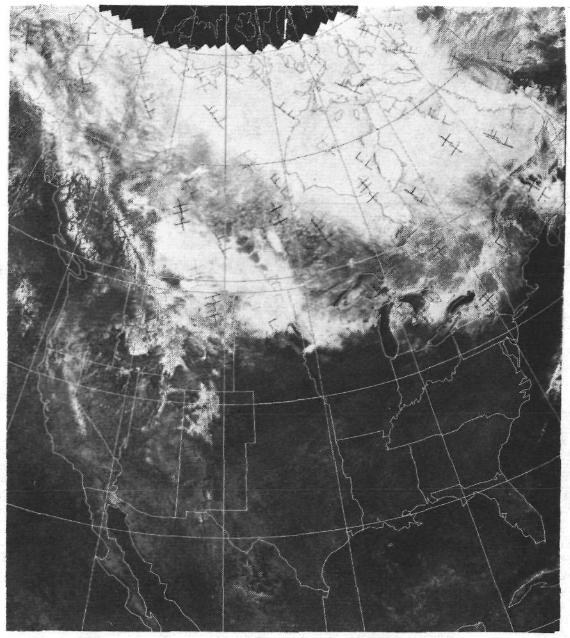

FIGURE 9. Five-day composite minimum-brightness mosaic removes most clouds, leaving snow and ice clearly visible.

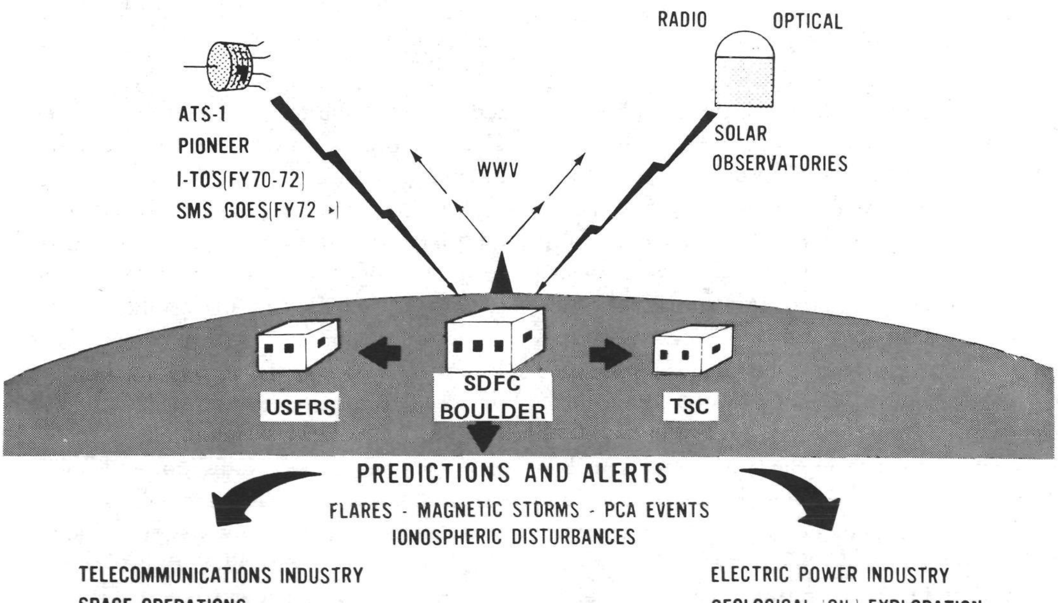

FIGURE 10. Schematic diagram of solar forecasting activities.

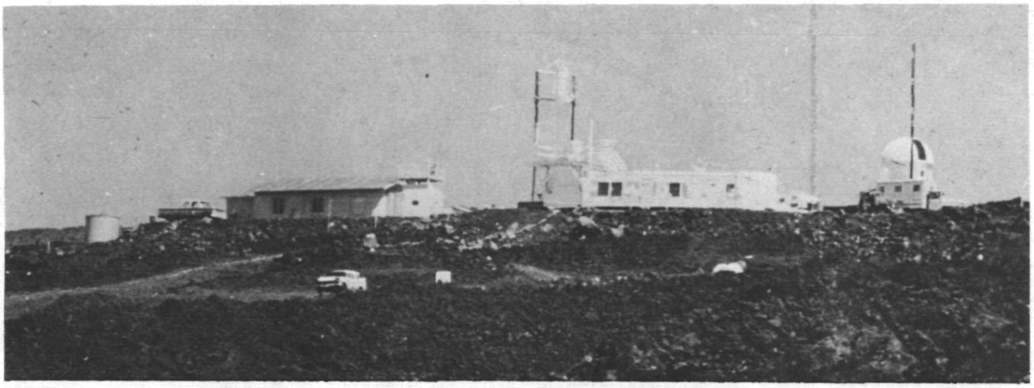

FIGURE 11. Mauna Loa climatic reference station.

an index of pollution, based on monthly averages, for each of the cities with the high-intensity light sources. These local index numbers could be combined in some form to produce regional and national indices, and finally a global index of pollution might be computed at regular intervals.

For the oceans, lakes, and coastal zones, we will be interested in other parameters. The positions and motions of large ocean currents have major effects upon climate throughout the world. General circulations of the oceans should be deducible from the sea slope produced by gravitational anomolies, measurement of which may be obtainable in the future from low-altitude drag-free satellites. Meteorological observations and measurements of sea conditions will give some indication of probable change in position of major currents, as well as the behavior of smaller currents. Sea surface temperature is an important parameter related to ocean quality, as are chlorophyll content and the presence of algae, all of which may someday be detectable with satellite sensors. Sea ice, another factor affecting ocean quality, can be observed by remote sensing.

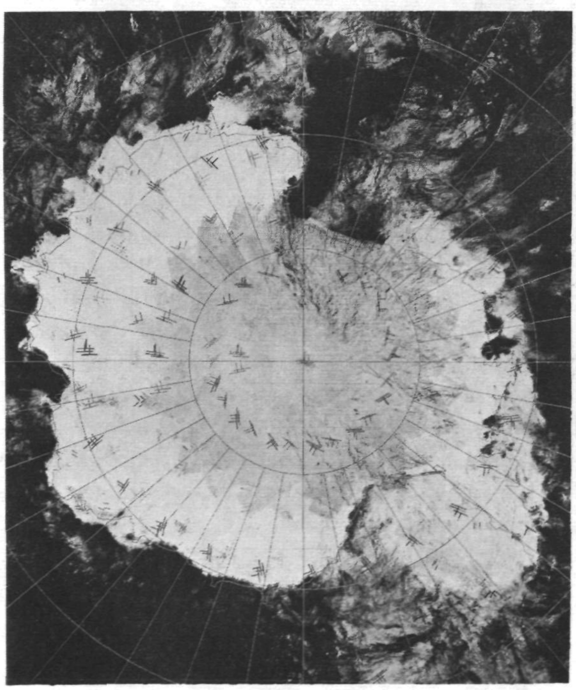

FIGURE 12. Five-day composite minimum-brightness photo of Antarctica.

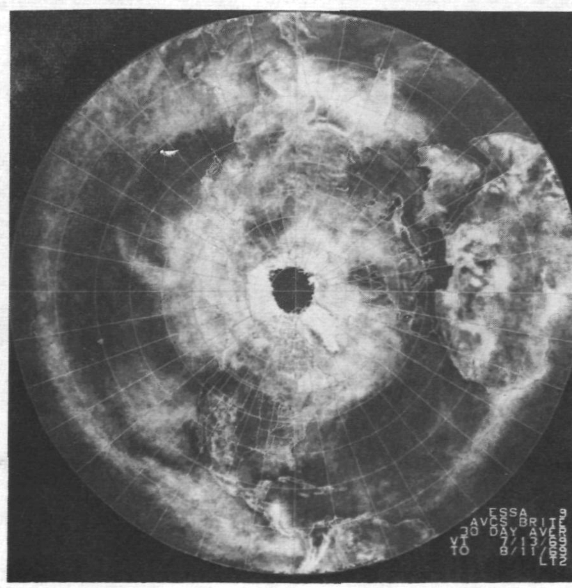

FIGURE 13. Thirty-day average-brightness composite shows mean cloud cover and precipitation over Northern Hemisphere.

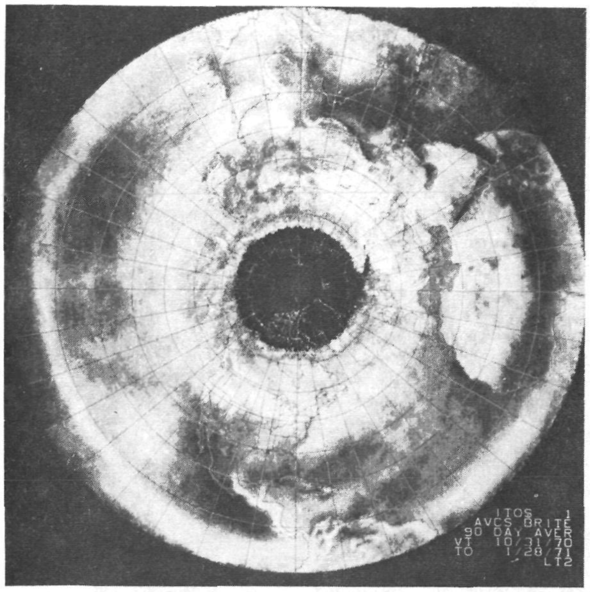

FIGURE 14. Ninety-day average-brightness composite shows mean cloud cover and precipitation for entire season.

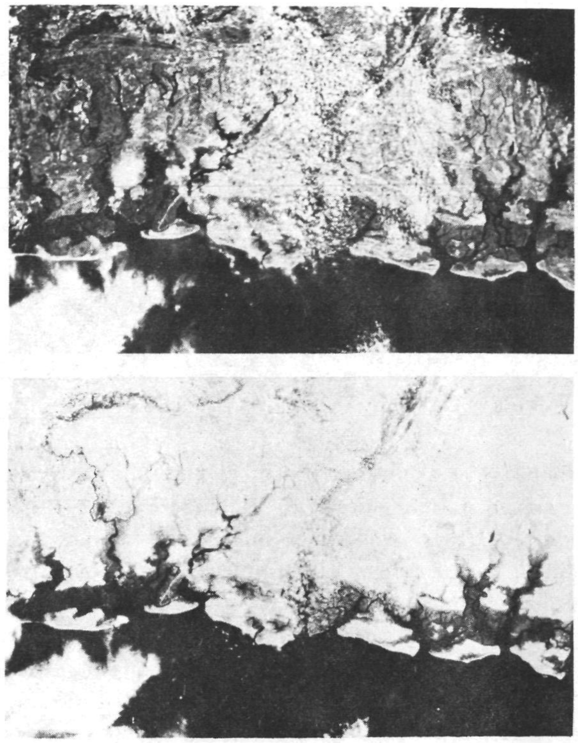

FIGURE 15. Infrared photoimagery identifies wetlands on Georgia coast in southeastern U.S.

Over the land areas of the world, another set of parameters will be of importance. We will be concerned with ice and snow cover; soil moisture and types of soils; nature, extent, and health of vegetative cover; and land use practices, all of which affect environmental quality and could be measured by aircraft and satellite remote sensors. The Earth's magnetic field may prove to play a significant role in environmental quality. It has been suggested, for example, that the Earth's magnetic field may be slowly reversing, in which case it would pass through zero at some future time. Since in the absence of a magnetic field solar particles would not be deflected, a dangerous rise in cosmic radiation harmful to human beings and other animals might then take place at the Earth's surface.

Finally, as has been suggested earlier, the irregular motion of the poles as the Earth rotates may bear an important relationship to major earthquakes and other seismic events.

The list I have given is far from complete, but it does suggest the great variety of measurements which may be necessary if we are to fully understand our environment and prevent its degradation. There seems little question that remote sensing from space and from aircraft is destined to play a major role in our attempt to preserve the global environment for future generations. Since we are all revolving around the same Sun together and the environment is global, I have no doubt that the problem of surviving on Earth can be approached only through a common effort of all nations working together. In the next few decades we may well face the greatest challenge to survival in the history of the human race. With the aid of remote sensing from space and from aircraft, let us dedicate ourselves to meeting that challenge.

Remote Sensing of Environmental Quality

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Man's progress during a particular decade is often labeled to indicate what happened during that period. In the case of the 1970's, a label was attached before the first year in the new decade was half over. So much emphasis has been placed on the future of the resources of this planet that the 70's are almost certain to be known as the Decade of Resources and the Environment.

During the last few years, through the eyes of astronauts, cosmonauts, and unmanned space vehicles, men throughout the world have had the opportunity to view our planet from an entirely new perspective. From hundreds and thousands of miles out in space, we have seen how finite this globe of ours really is. Using this new perspective, we must now consider how to monitor and direct our future activities so that we can insure that many more generations will be able to survive on this planet with some degree of comfort.

Many people have gone to great lengths to illustrate what our present problems are and what they will be in the future. This exercise could appropriately be termed the "pessimistic phase" of our new environmental concern, where one selects a subject, gathers statistics, examines predictions, and arrives at the inevitable conclusion that man is in serious trouble if he continues to misuse his technology and his environment. But it is this same technology that is the key to monitoring and improving the environment. It is time to enter a second phase of environmental awareness—to begin presenting a positive approach to assessing and improving environmental quality.

An excellent way to accomplish this task is through the use of remote sensing. Remote sensing, it should be remembered, applies to a series of related activities. It includes not only the selection of appropriate instruments, but data collection, processing, distribution, and analysis. Furthermore, as stated in the *NASA Training Course in Remote Sensing*, prepared by the Willow Run Laboratories of the University of Michigan, remote sensing is based on inference (e.g.: "If cause C_1 exists, then effect E_1 will be observed; and if effect E_1 is observed, then cause C_1 must exist"). This cause-and-effect relationship is exactly what environmental quality assessment involves and is effectively illustrated by figure 1.

In trying to assess the quality of an environment, it is sometimes easiest to single out the negative aspects. This practice is being followed throughout the world today whenever someone studies or discusses pollution. Recently, the Geographic Applications Program of the U.S. Geological Survey (USGS) completed a study entitled "Remote Sensing of Environmental Pollution." This work was done as a special project for the Department of the Interior's Earth Resources Observation Systems (EROS) Program and for the Earth Observations Program of the National Aeronautics and Space Administration (NASA). The intent was to illustrate the capabilities of various remote sensing devices to detect, identify, measure, monitor, and determine the effects of environmental pollution.

Samples of remotely sensed data were classified as water, air, or land pollution, and within each category an attempt was made to illustrate what can be observed and/or monitored from current spacecraft, high- and low-altitude aircraft, and ground-based platforms. Examples of data from a variety

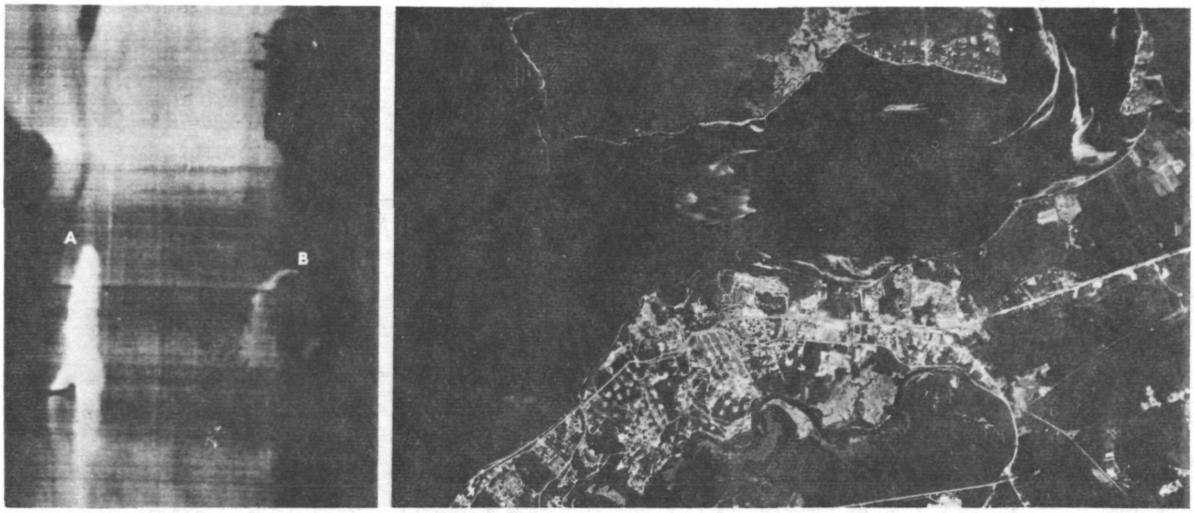


FIGURE 1. Cause-and-effect relationship. The thermal infrared imagery on the left has detected two effluents in a river. The effluent at A is from a sewage plant and is decidedly warmer than the river. The effluent on the right is hot water being discharged from a power plant at B. The sewage plant is one of several along this river and, like most municipal sewage plants, is currently overloaded and must often discharge raw or partially treated sewage into the river. The effect of this is quite evident on the color infrared photograph on the right. This photograph was taken several miles downstream from the effluents and clearly shows how algae are now growing from one bank of the stream to the other. Thus an inference can be made that if cause C_1 (sewage and hot water) exist, then effect E_1 (algae) will be observed, and if effect E_1 (algae) is observed, then cause C_1 (sewage and hot water) may exist.

of remote sensing instruments and of special processing, enhancement, and analysis techniques were also included.

During the tutorial portion of this workshop, some of the 125 illustrations contained within the report will be examined and discussed in detail. These illustrations cover more than 50 of the environmental problems faced by this Nation. Some of these may be problems in your country, while others may not be; their extent and the ability to recognize and cope with each of them will vary from country to country. What one nation determines to be a critical environmental problem may not be considered critical by a neighbor and, in fact, may rate a much lower priority in terms of that nation's overall goals. However, as nations continue to industrialize, they must learn from each other, assist each other, and establish practices that will make an acceptable quality of environment practicable.

To show how action can be stimulated to improve environmental quality through the collection, analysis, and use of remotely sensed data, a series of steps and procedures can be outlined and used as guidelines to show how remote sensing can be used to accomplish the following objectives:

1. Collect data for land use mapping.

2. Detect alien substances in the environment.

3. Identify specific pollutants and classes of pollutants.

4. Measure varying concentrations of pollutants through time.

5. Monitor the source, movement, and fate of pollutants.

6. Determine the effects of pollutants on the environment.

7. Analyze remotely sensed data to determine environmental quality, determine the susceptibility of the environment to degradation, and provide data for comprehensive environmental planning and modeling.

STEPS AND PROCEDURES

The following steps and procedures are intended to serve as suggested guidelines for conducting a regional environmental quality study. They illustrate how a logical, orderly process should be followed so that all the potential as well as current environmental problems can be located and defined. By following these guidelines or variations of them, according to capabilities and resources available, it is possible to carry out studies in different areas and obtain consistent results.

Step 1. The first step in this regional study is to define the area to be surveyed and then to collect whatever environmental data are available. This would include such things as geologic maps, soils maps, topographic maps, climate and weather data, recreation plans, utilities maps, etc. Such data are usually referred to in a remote sensing program as ground truth information and represent the first step in gaining an understanding of a region.

Step 2. While ground truth is being collected, a set of high-quality aerial photographs of the area should be acquired. Experience with NASA's Earth Resources Aircraft Program has demonstrated that medium-to-high-altitude (6 to 18 km) color infrared coverage, with either a 150- or 300-mm-lens metric camera, can provide the best data. Color infrared is extremely useful, since it penetrates haze better than color emulsions, can be used effectively to make black-and-white prints, is best for discriminating various land uses, and provides clues as to the health and vigor of various types of vegetation.

Step 3. After the aerial photography has been acquired, it is advisable to prepare controlled mosaics of the coverage. Mosaics are made by piecing together the strips of photography that cover the study area, thus creating a photographic "map" of the region. Users find that it is easier to relate to a photomosaic than a map because of the increased number of identifiable features. This type of product is also an excellent storage medium for geodetic positioning information. Such mosaics have proved useful in various USGS and NASA projects. An example of part of a controlled mosaic of Washington, D.C. is shown in figure 2D. The white grid superimposed on this mosaic is the 1-by-1-kilometer Universal Transverse Mercator grid used to plot and/or extend positioning data. Parts A, B, and C of figure 2 show the test site map, flightline map, and camera coverage diagrams for a mission flown over Washington, D.C. as part of a research program to develop an atlas of land use changes for each of the cities or regions shown on the map. This program will be discussed in detail during the second week of the International Workshop.

Step 4. Since it is necessary to know where people are located and in what numbers, a fourth step is to plot census tracts at the same scale as the mosaics and aerial photography. A census tract is a standard area used by the U.S. Bureau of the Census for purposes of locating population totals. While tract specifications may not be standard throughout the world, many nations use a variation of them to locate people counted during each census. Figure 2E shows the census tracts and numerical indicators for part of the Washington, D.C. area.

Step 5. The fifth step in an environmental analysis may require the use of photo interpreters, discipline scientists, or remote sensing specialists. This step involves the preparation of a land use map of the area, as shown in figure 2F. The various colors on the map represent the different kinds of land use or activity in the study area. It might indicate where such things as industrial areas, garbage dumps, sewage plants, parks, and recreational facilities are located. By measuring these areas, it is possible to determine how much land area is devoted to each activity.

Whenever a project requires land use mapping, there is always a question of what scale or level of information is required. Does the requestor want to know where a particular type of industrial plant is, or does he want to know where all industrial plants are? Is he interested in a small group of trees or the entire forest? This is true of remote sensing of environmental quality. While it may be necessary to photograph in detail a particular negative or positive aspect of the environment, such as a sewage plant effluent, one still needs to know what its place is in the total environment. To get this picture you need so-called synoptic or small-scale data. This data can be acquired from satellites as shown in figure 3, by high-altitude aircraft, or by using a short-focal-length camera from lower altitudes.

This type of land use information can be ex-

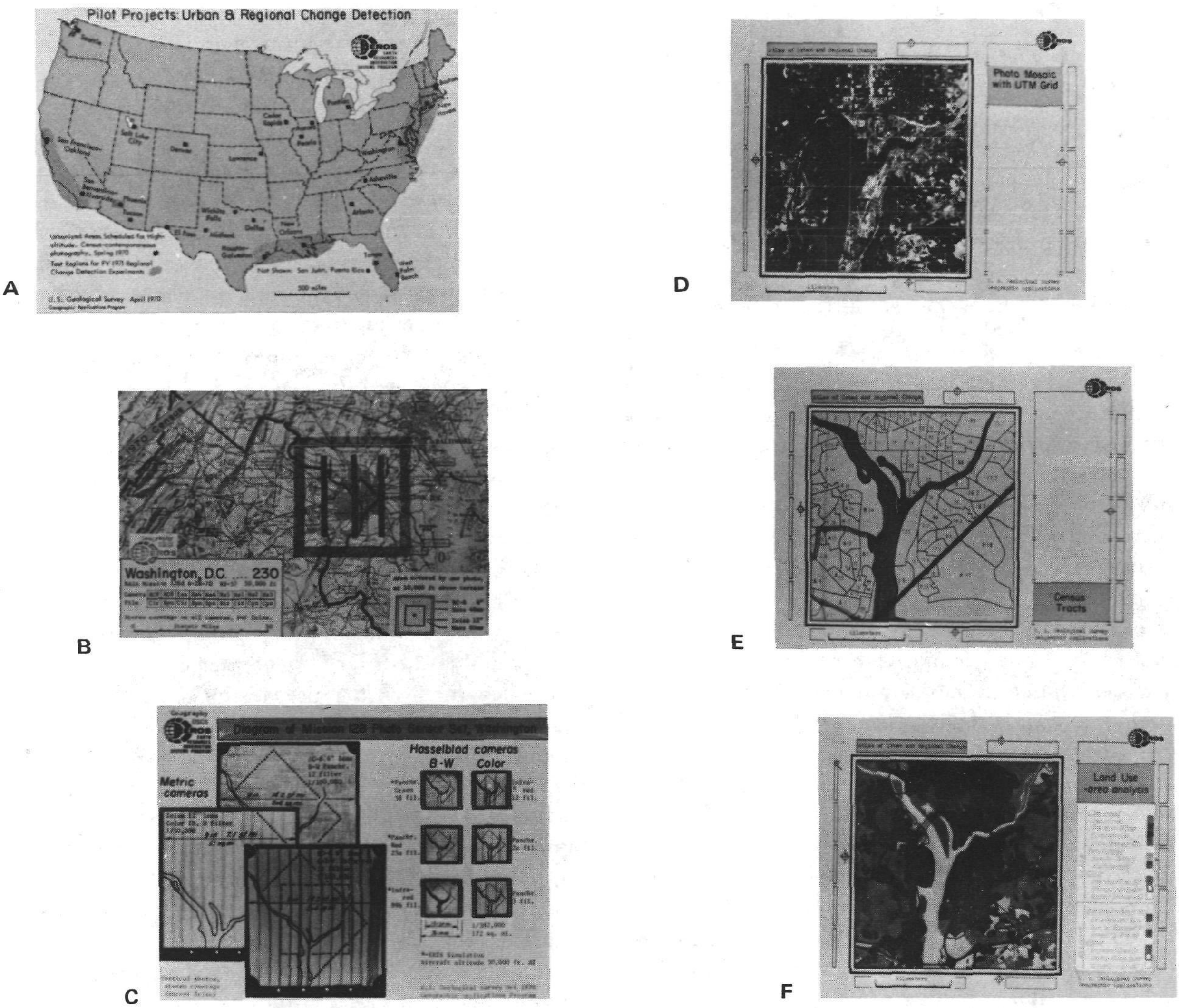


FIGURE 2. Elements of Census Cities Project and *Atlas of Urban and Regional Change.*

tremely useful to various people besides those conducting the environmental analysis, and in most cases it is usually collected for reasons other than to determine environmental quality. Health officials, for example, may wish to know where all the wetlands are so that they can adequately fight mosquitoes and thus cut down on the incidence of malaria. Planners must know whether they are allowing their cities to expand over the best agricultural soils, while allowing the poorer areas to go undeveloped. People concerned with pollution will want to know where industries are located so that they can determine which streams will probably be carrying industrial byproducts. Synoptic studies provide the basis for determining where detailed work should be carried out and eliminate the troublesome task of collecting vast quantities of large-scale data only to find that just a few photographs are useful.

Step 6. Once the first five steps have been completed, one can begin extracting the specific information concerning the detection, identification, and monitoring of environmental pollutants. By careful examination of the photography and use of stereo and microscopic devices, interpreters can effectively carry out a cataloging and inventory of effluents, sewage plant locations, smokestack plumes, etc. By plotting this data along with such things as the

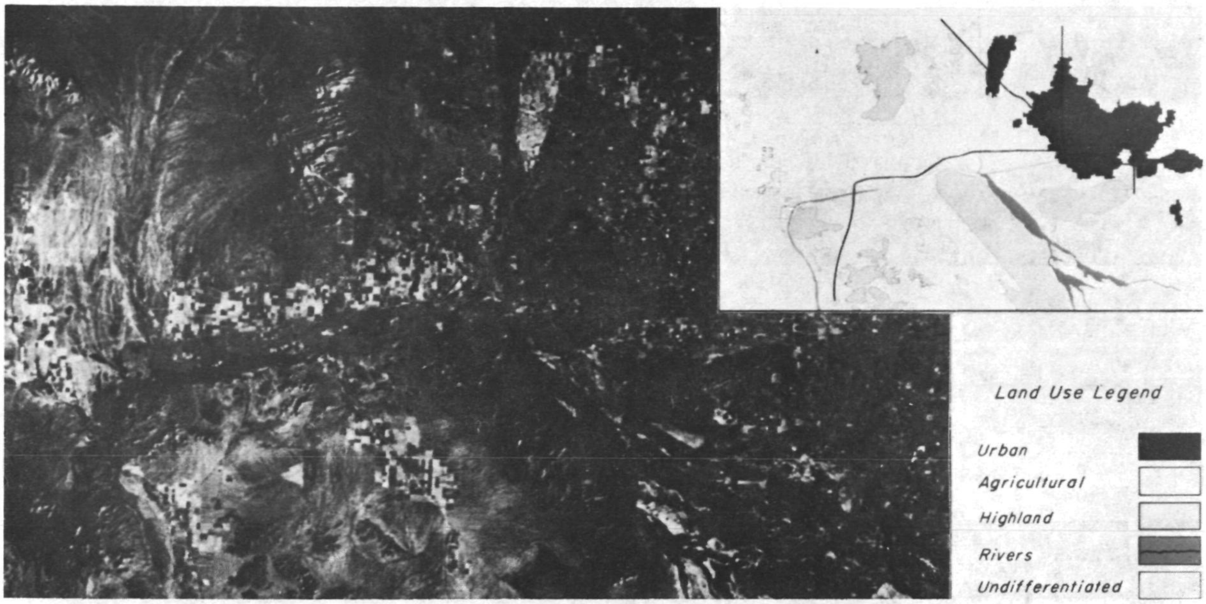


FIGURE 3. Mapping metropolitan land use from Apollo color IR photography.

location of heavy industry, automobile junkyards, etc., which may already have been located during the preparation of the basic land use overlays, a base map of pollution sources and indicators can be compiled.

Once the basic photographic coverage has been analyzed, the requirements for further photography will become obvious. It is at this point that special sensors, altitudes, and film/filter combinations will be required. For example, it is highly recommended that an infrared or multispectral line scanner be flown over the major river systems in the region. These data will provide information from the ultraviolet to the infrared portion of the spectrum and detect and record such things as oil spills and thermal effluents. Figure 4 illustrates what varied detections can be made with a multispectral scanner.

Another problem that will arise is the need for time-variance or change-detection data. Figure 5 shows how coverage over a particular effluent changed with time and allowed interpreters to identify it as coming from a nearby textile plant. Thus the pollutants were not only detected, but also identified and monitored through time. From these observations, certain conclusions can be drawn regarding the movement and fate of pollutants and what areas will be affected by their presence. With effluent data for determining the vertical profile, plus knowledge of the areal extent of the plumes on the photographs, it is also possible to make an estimate of concentrations.

It may also be very important to have seasonal coverage, especially if there is only one set of aerial photographs over the region. An excellent example of why this is important is shown in figure 6. This illustration shows how early spring coverage detected the secondary effects of a ground water system contaminated with municipal sewage. It is an excellent example of how remote sensing detected the effects of a pollutant on an environment before the pollutant itself was seen or identified.

Many other specialty sensors could be employed in a study area. They include such things as a scintillation detector for radiation problems, a decibel recorder for environmental noise, microwave radiometers for temperature studies, and a variety of instruments that can be operated on the ground. A Fraunhofer line discriminator for detecting substances that fluoresce and a correlation spectrometer for measuring quantities of air pollutants are currently undergoing research and development tests and may soon be available. Examples of these instruments will be discussed in the second half of this workshop.

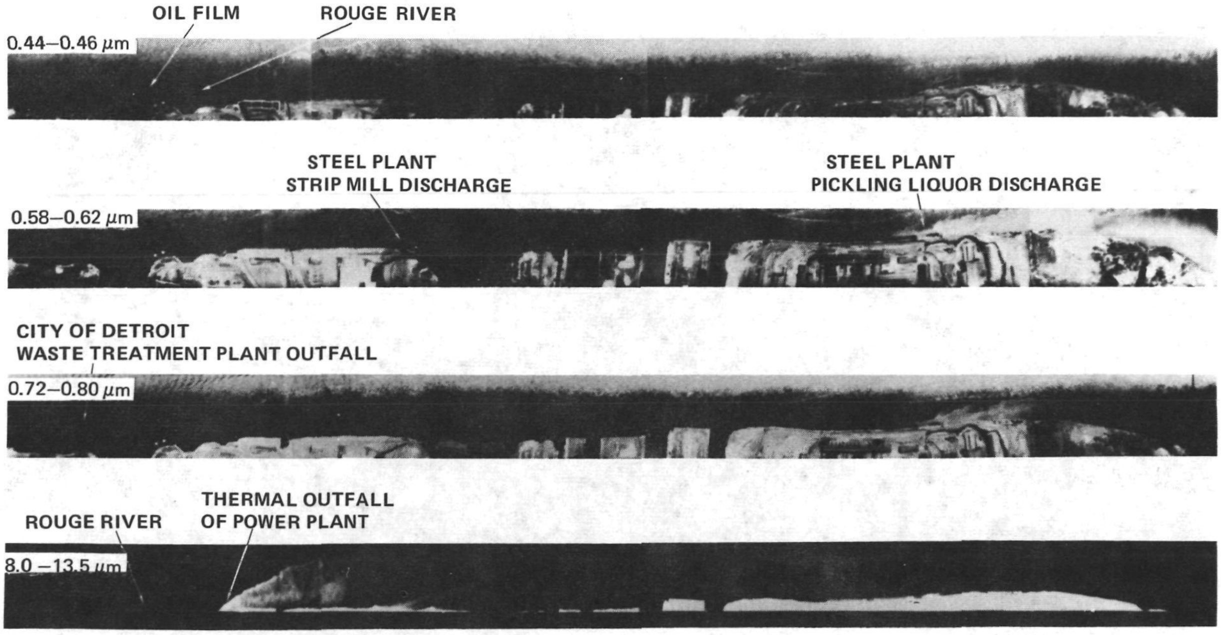


FIGURE 4. Multispectral scanner imagery. A multispectral scanner was flown experimentally along the Detroit River to see what the various channels could detect. The Detroit River is bordered by heavy industry and is a likely place to locate industrial pollutants. A cursory examination of the four images reveals many differences between them. On closer examination, the interpreter can detect oil pollution from the Rouge River in the 0.44-to-0.66-μm image; two different steel mill discharges in the 0.58-to-0.62-μm images; a sewage treatment plant outfall in the 0.72-to-0.80-μm image; and the thermal effluent from a power plant in the 8.0-to-13.5-μm image. These preliminary experiments are encouraging and may lead to automated image analysis.

Step 7. To facilitate analysis of the remotely sensed data, several photographic and color enhancement processes should be investigated. Figure 7 shows how thermal infrared imagery over a nuclear power plant effluent can be improved by color enhancement, and how a boresighted radiometer can provide temperature data at the same time the thermal infrared imagery is acquired. Figure 8 shows how a microdensitometer can be used to break down the subtle surface temperatures of a thermal plume. Data of this sort is useful in determining the extent and fate of thermal effluents and for indicating where sampling devices should be placed. Figure 9 illustrates results of the process of density slicing. The individual color photos show how an original black-and-white photograph has been quantified into five discrete bands corresponding to the density, or grey shades, on the original imagery. Each density level is then printed in a different color and combined to form the composite photo in the upper left corner.

These are but a few of the ways remote sensing data can be exploited to produce environmental information. Even more sophisticated techniques are being explored to allow a computer to compare multispectral imagery of specific pollutant images or signatures. In fact, it is eventually hoped that a signature data base can be established for various types of pollutants.

Step 8. The next step in determining environmental quality is to establish an information system and a working model for the region. This involves the use of a computer to store the available environmental information on a particular region. Each new set of data may then be entered and compared with previously collected data. Out of this comparison may come new information on which to base conclusions regarding environmental quality

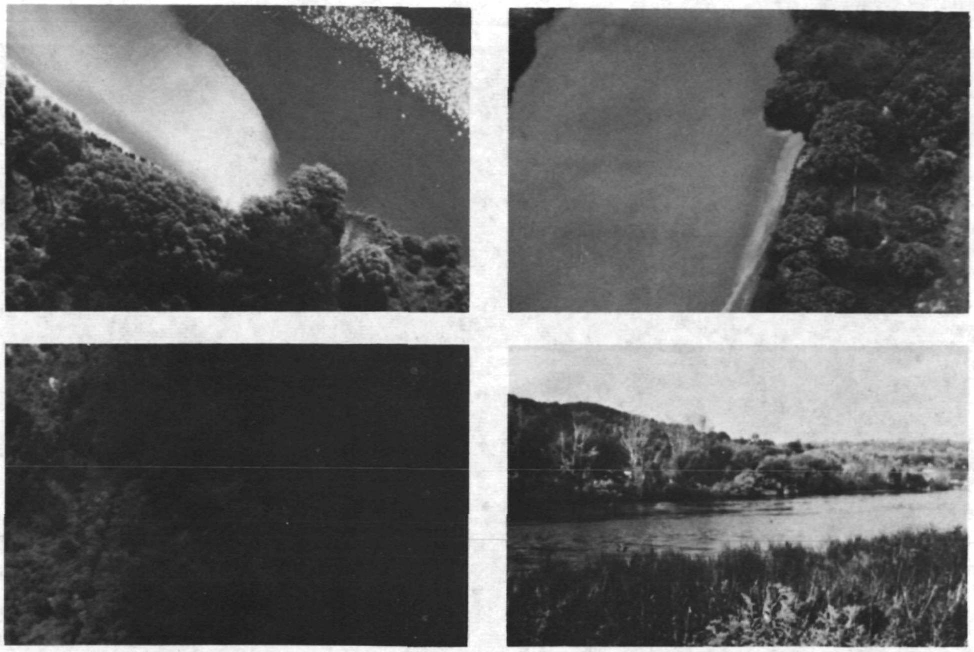


FIGURE 5. Change detection data. The three low-altitude color photographs in this figure were taken during a period of several weeks over the same area. Analysis of the first photograph (upper left) suggested that the discharge might be raw sewage, but subsequent coverage disclosed color changes in the effluent and allowed interpreters to identify the source as a nearby textile plant. The ground photograph (lower right) was taken across the river from the effluent at a time when a blue liquid was being discharged. This is not evident on the photograph and shows the value of aerial monitoring.

assessment. For example, if someone wishes to know what the phosphate content of a certain stream is, a researcher could check to see how much fertilizer containing phosphate has been purchased in the area; next, he could check the land use overlays to see where the agricultural areas are; then he could check the average rainfall and ground slope conditions to determine where phosphate runoff might occur; he also could check on the sewage plants in the area to see what percent of phosphates they are treating or allowing to be dumped into the rivers; and finally, he could update this information with any new data or changes. From all of this data he should be able to suggest what the phosphate pattern of the stream is likely to be and to show where sampling devices should be located to provide specific information. The same procedures can be used to compute how much garbage and waste will be produced in a certain region or how many junked automobiles may exist from one year to the next. In this way, environmental planners and decision makers can have better information on which to make land use decisions and, in turn, improve environmental quality.

Step 9. The final step in a regional environmental quality study is to initiate corrective programs and practices. This involves decisions which must be made by administrators, resource managers, ecologists, planners, developers, etc. The first eight steps outlined in this paper can provide information on which to base most of these decisions. Once corrective actions have been taken, it will probably be of interest to these decision makers to monitor the region for assessing environmental improvements and/or violations. This, of course, can be accomplished with remote sensing. Thus, if periodic remote sensor coverage is acquired, it can be used not only to produce new data to be analyzed and

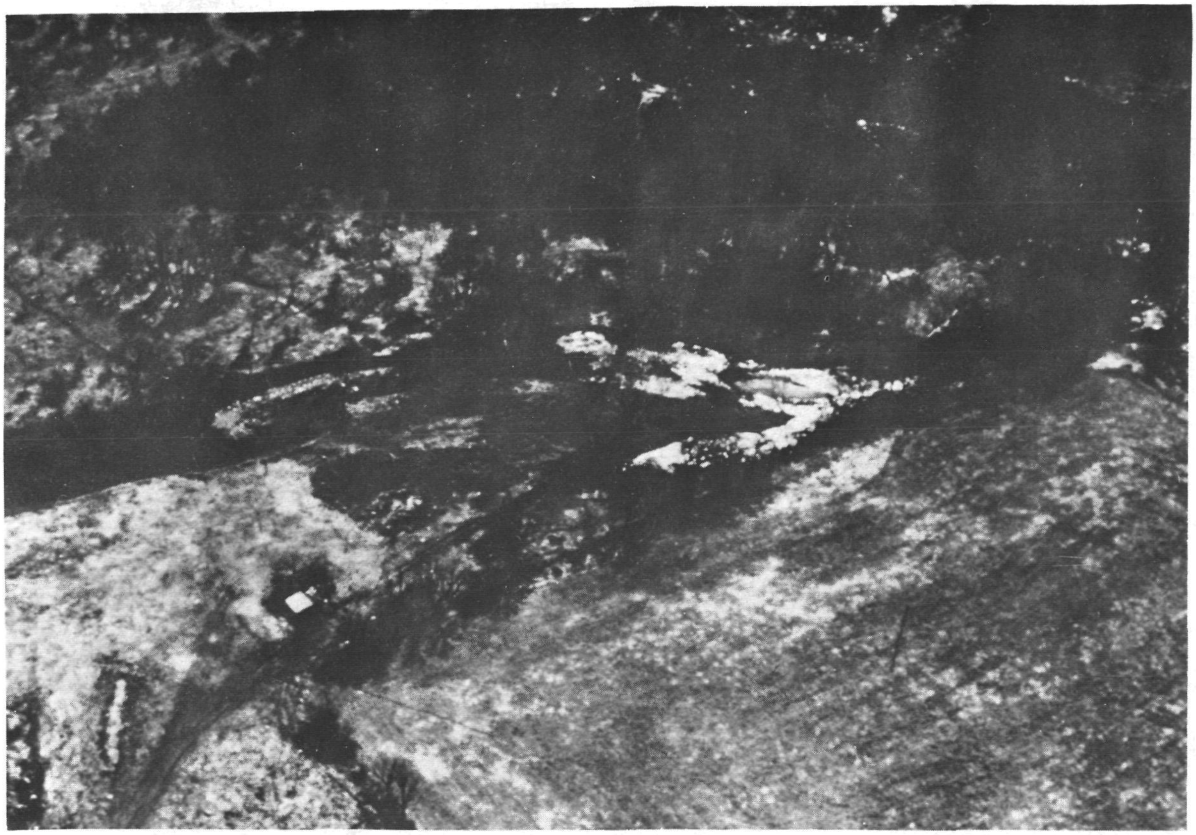


FIGURE 6. Importance of seasonal coverage. The photograph above illustrates the importance of seasonal coverage and how remote sensing can be used to detect a secondary effect of a group water system contaminated with sewage. Upstream from where this photograph was taken a small community has been dumping its sewage into a system of sink holes, thus contaminating the ground water system and several springs that feed this stream. The color infrared photograph was taken in March and there is snow on the ground, but because the contaminated water is warm and full of nutrients, it has caused an early growth of vegetation along the edges of the stream system. Thus, by photographing rivers and streams early in the spring, it may be possible to detect the secondary effects of this type of environmental pollution when otherwise it might go unnoticed.

entered into the information system, but it can also be used to assess the success or failure of the corrective action programs and practices.

CONCLUSIONS

Man has never lived in blissful harmony with nature, and nature has seldom provided the perfect home for man by his own definition. There have always been elements in the environment which were undesirable and beyond his control, such as specific occurrences of algae, salty water, acid water, volcanic dust, smoke, and silt. These cannot be categorically classified as pollution, because they are products of natural processes but, on the other hand, man must be capable of coping with these byproducts of nature. Our society has removed or greatly modified certain aspects of the natural environment and ignored many others. By stimulating or restricting natural processes and increasing his consumption rates, modern man is locally overburdening his environment and, in so doing, is causing pollution and degradation of environmental quality.

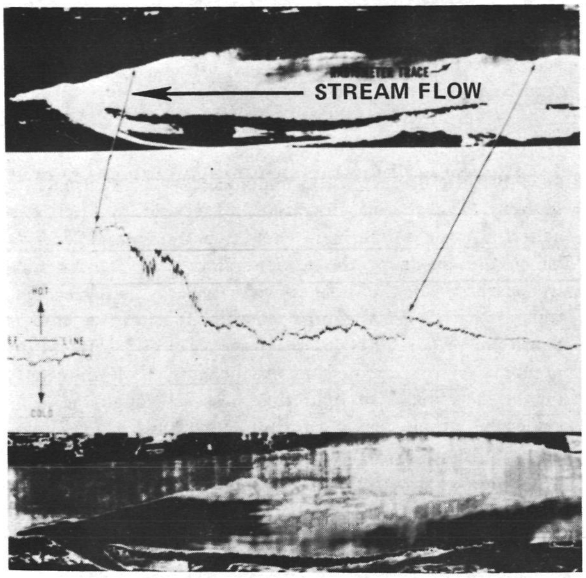


FIGURE 7. Color enhancement of thermal IR imagery. The thermal IR imagery shown at top was collected over the effluent of a nuclear power plant. The radiometer trace (center) registered a rise in temperature of 8 °C at the point where the river and the hot water meet. The grey tones of the imagery were then converted into colors (bottom) to aid in the discrimination of surface temperature patterns. It should be noted that an incoming tide has carried the hotter water upstream past the channel mouth where the effluent enters the river. This creates a problem in the normal dispersal and dissipation of heat in the river.

Remote sensing can help provide the data that man must have to guide him in the future. Environmentalists, planners, health officials, fishermen, industrialists, educators, students, scientists, and government decision makers will one day have to rely to a great extent on these types of data to tell them what is happening to the natural and physical Earth that sustains us. As mentioned in this paper, one way to secure regional data on which to make environmental quality assessments is through the use of remote sensing according to the following nine steps that have just been discussed.

1. Collect environmental information relating to the study region.

2. Acquire high-quality aerial photography of the region.

3. Prepare controlled mosaics of the photography.

4. Collect census data and plot this information on mosaics.

5. Prepare a land use map of the region.

6. Extract and plot all identifiable sources and potential sources of land, air, and water pollution.

7. Employ special analysis and enhancement techniques to increase the level of information extraction.

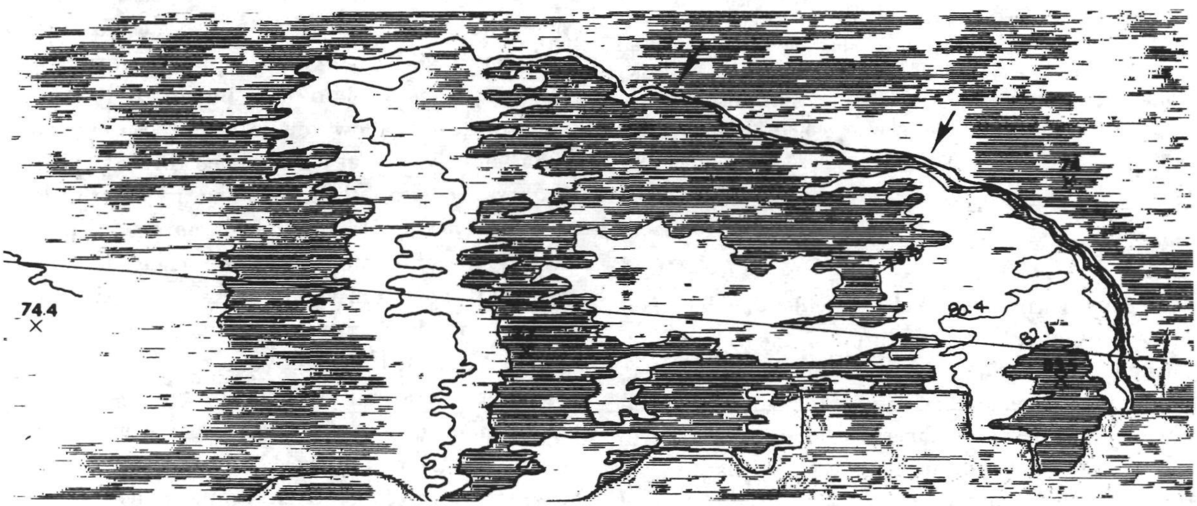
8. Establish an information system and working model for the region.

9. Initiate corrective action programs and practices.

Although it is desirable to approach a regional environmental quality study according to the nine steps discussed in this paper, environmental quality can be assessed without having to complete each and every step. If, for example, you cannot acquire controlled mosaics, an uncontrolled mosaic or standard map could be used to show the various land use categories or sources of pollution. If your resources do not allow you to acquire special sensor data, employ special enhancement or analysis techniques, or establish a computerized information system, you should not be discouraged from collecting aerial photography and using it in your study. If your census data are not available by tracts, you may wish to eliminate this step completely. In other words, your financial and technical resources will probably be the best indicator as to which of the nine steps you are able to complete. However, for most regional environmental assessment programs it is recommended that steps 1, 2, 5, 6, and 9 be undertaken.

Remote sensing is a tool, or a source of information, but it will not solve each and every problem. It must be understood, interpreted, and carefully used before it can provide many of the answers that users desire of it. In a remedial context its use is direct, in that it consists of locating and monitoring; in a preventive context it is indirect, since it can only point out potential problems on the basis of previous detections.

FIGURE 8. Microdensitometry enhancement of thermal IR imagery. The thermal infrared imagery at the left was collected over a thermal electric power plant. To enhance the image of the effluent from this plant a film transparency of the imagery was scanned with an extremely small light source contained within a microdensitometer. In this process very subtle temperature gradients can be defined, as on the graph below, according to the amount of light that passes through the film. Once the graph has been completed and surface temperature samples plotted (indicated by X's), temperature contours of the surface layer of hot water can be drawn.



Today there is talk of worldwide pollution problems and what modern man is doing to ecological cycles. Nations must move toward establishing international monitoring and analysis programs, and remotely sensed data could prove to be the linking element in such efforts. Cooperative aircraft programs and the availability of Earth Resources Technology Satellite data could be two important steps toward establishing a quality environment throughout the world.

What are the environmental problems in your country? What potential problems will you have to face? What is your role in the international monitoring programs? Can you, or should you, use remotely sensed data to help solve your problems? These are questions that each of you should keep in mind and seek answers to, during the next week and when you have departed from this International Workshop on Earth Resources Survey Systems.

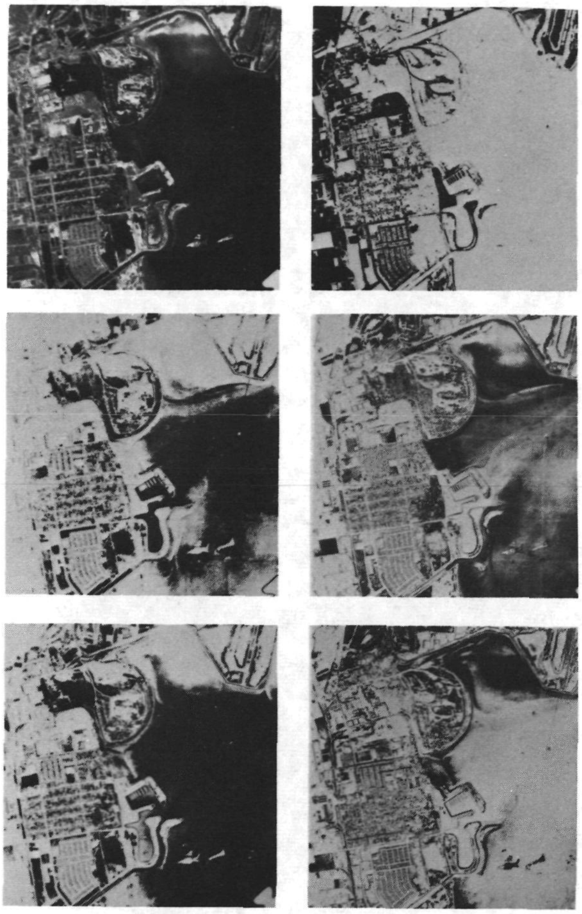


FIGURE 9. Density slicing. The photographs in this figure are reductions of six color separations of a single green-band black-and-white photograph. The original photograph has been quantified into five discrete spectral bands corresponding to the density, or grey shades, on the original image. Each level is then assigned a color and printed on a transparent material so that they can be combined in various combinations as illustrated by the composite photograph in the upper left-hand corner. Collateral ground checking indicates that the bright yellow color in the upper part of the photograph is related to sewage in the water and the bright red or purple color is oil lying on the surface of the water.

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SESSION III

Chairman: John W. Townsend

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The Earth Resources Survey Flight Programs

ARCH B. PARK
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In the Earth Resources Survey Program of the National Aeronautics and Space Administration (NASA), three space flight experiments are planned: the Earth Resources Technology Satellite A (ERTS-A), scheduled to be launched in March 1972; the Earth Resources Experiment Package (EREP) of the manned Skylab orbital facility, scheduled for launch in April 1973; and ERTS-B, scheduled for launch in May 1973 (figure 1).

These experimental flights will collect sensor data which may be applied to research in agriculture, forestry, ecology, geology, geography, meteorology, geomorphology, hydrology, hydrography, oceanography, and other fields for the purpose of identifying agricultural species; measuring growth rates; assessing crop vigor and stress; classifying land use; determining land surface composition and structure; mapping snow cover and assessing water runoff characteristics; mapping pollution, shorelines, and estuaries; evaluating sea roughness conditions; and similar projects. Proposals to investigate automatic data processing techniques and instrument performance (such as the altimeter) will also be considered. ERTS-A and B will be placed in a Sun-synchronous near-polar orbit at an altitude of 910 km.

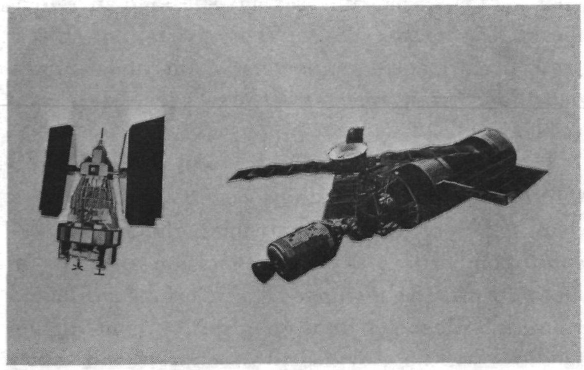

FIGURE 1. The newest Earth observation satellites: ERTS (left) and Skylab.

DESCRIPTION OF SPACE SYSTEMS

The ERTS-A and B sensor payload consists of (1) a multispectral TV system using return-beam vidicon (RBV) cameras, (2) a multispectral scanner (MSS) system, and (3) a data collection system for collecting data from sensors at known locations on the Earth. The RBV cameras are sensitive to the following wavelengths: camera 1, 0.475 to 0.575 μm; camera 2, 0.580 to 0.680 μm; camera 3, 0.690 to 0.830 μm. The average ground resolution per TV line ranges from 50 meters for high-contrast scenes (desert sand vs. shadow) to 85 meters for low-contrast scenes (vegetation vs. dark soil).

The MSS is sensitive to the following wavelengths: band 1, 0.5 to 0.6 μm; band 2, 0.6 to 0.7 μm; band 3, 0.7 to 0.8 μm; band 4, 0.8 to 1.1 μm; band 5, 10.4 to 12.6 μm (ERTS-B only). Comparable ground resolution for the scanner is approximately 80 meters, except for band 5, which is 220 meters.

The bulk data processing operation consists of conversion of recorded video signals from the RBV cameras and the multispectral scanner to photographic film, plus addition of suitable annotation to these images. The processing operation also includes processing of spacecraft housekeeping telemetry for the purpose of extracting camera shutter times, sensor calibration information, and spacecraft attitude. The computation of spacecraft attitude and geographic coordinates of image centers is also a major data processing operation. Selected image

sets will be digitized, registered, rectified, and converted to some standard map projection system, e.g., Universal Transverse Mercator.

The Data Services Laboratory (DSL) for ERTS-A and B will provide users, principal investigators, project personnel, and archives: (1) RBV and MSS bulk images (to user agencies and investigators); (2) RBV and MSS digitized data (per arrangement with user agencies and investigators); (3) RBV and MSS precision-processed images (per arrangement with user agencies and investigators); (4) data collected from platforms, listings, or digital tapes (per arrangement with user agencies and investigators); (5) master digital tapes containing spacecraft performance parameters, orbit and attitude data (per arrangement with user agencies and investigators).

The ERTS photographic lab will be established to provide: (1) master and second-generation negatives, (2) positive transparencies and prints, (3) color composites, (4) high-precision imagery in many forms, (5) montage catalog prints and bound volumes. Magnetic tape duplication and listing facilities will be provided to produce second copies of recorded analog and digital tapes.

Skylab will be a solar-pointing, inertially stabilized spacecraft. To use the EREP sensors, Skylab will be maneuvered to an Earth-oriented mode. A minimum of 45 maneuvers are planned for the 8-month mission. Specific sensors under development for Skylab (EREP) are as follows:

S–190—A six-band multispectral photographic facility using 70-mm film. The wavelength response of the S–190 is as follows: camera 1, 0.5 to 0.6 μm; camera 2, 0.6 to 0.7 μm; camera 3, 0.7 to 0.8 μm; camera 4, 0.8 to 0.9 μm; camera 5, 0.5 to 0.88 μm; camera 6, 0.4 to 0.7 μm. The lenses will have a focal length of 15.2 cm (21.2° field of view across flats), providing an approximately 163-km square surface coverage (26 600 km^2) from the 435-kilometer orbit.

S–191—A filter-wheel infrared spectrometer which covers the 0.4-to-2.4 and 6.2-to-15.5.-μm bands.

S–192—A multispectral scanner operating in the band from 0.4 to 12.5 μm. The wavelength response (in μm) of the S–192 is as follows: (1) 0.410 to 0.460; (2) 0.460 to 0.510; (3) 0.520 to 0.556; (4) 0.565 to 0.609; (5) 0.620 to 0.670; (6) 0.680 to 0.762; (7) 0.783 to 0.880; (8) 0.980 to 1.080; (9) 1.090 to 1.190; (10) 1.200 to 1.300; (11) 1.550 to 1.750; (12) 2.100 to 2.350; (13) 10.200 to 12.500. The sensitivity (noise equivalent reflectivity) of the visible and reflective infrared bands will be about 1 percent, and the sensitivity (noise equivalent temperature) of the thermal band will be 0.4 K. Each band will have an instantaneous field of view of 80 meters square.

S–193—A microwave radiometer/scatterometer and altimeter facility operating near 13.9 GHz.

S–194—A passive L-band radiometer operating near 1.4 GHz.

All data will be cataloged, indexed, and entered into an information storage and retrieval system. Lists will be published showing the data existing from the Skylab EREP and other Earth Resources Survey Program-acquired data. Maps will be prepared to show the flight track and area covered by each sensor for all approved test sites.

Data packages will be formed for each approved investigator, containing the following items as appropriate for his investigation: film from S–190 and S–191 (positive and/or negative); quick-look film and digital CCT's of S–192 data; digital tapes, plots, and tabulations of S–193 and S–194 data; flight logs; best-estimate trajectory; voice transcripts versus time; mission anomalies versus time; and maps of flight track showing coverage.

All S–190 film will be annotated to show coordinates of the principal point and corner points of the photograph (latitude, longitude), time, altitude, wavelength band of photo, film type, exposure time, f-number, density and gamma used for processing, filter, and generation of the copy.

NASA's Earth Resources Aircraft Program (ERAP) is directed primarily at testing a variety of remote sensing instruments and techniques in aircraft flights over preselected test sites mostly in the continental United States, although sites in other countries and geographic areas (such as the Gulf of Mexico, the Caribbean Sea, the Atlantic Ocean, and South America) are also chosen as the occasion warrants.

THE EARTH RESOURCES AIRCRAFT PROGRAM

The ERAP presently includes three aircraft, operated and scheduled out of the Manned Spacecraft

Center (MSC) at Houston, Texas. They are the NP–3A, NC–130B, and RC–57B aircraft. In addition, MSC coordinates the scheduling and operation of a C–47 contract aircraft operated by the University of Michigan. The program has recently been augmented by the acquisition of two U–2 aircraft, to be managed by the Ames Research Center with primary basing at Moffett Field, California, for the high-altitude acquisition of ERTS simulation data. From time to time other NASA aircraft or aircraft of other agencies fill in to meet specific program needs. The ERAP aircraft and sensor systems are described below.

NP–3A (NASA 927)—A version of the Lockheed P–3A Orion, this aircraft was acquired on loan from the Navy in December 1965 and became operational in 1967. Its function is to acquire data from low and intermediate altitudes, and it is heavily involved in obtaining oceanographic data.

The NP–3A is a four-engine turboprop aircraft with an operational ceiling of 7.5 km and an endurance of 6 hours at altitude, approaching a 3200-km range. It can attain airspeeds of 275 to 610 km/h and carries a three-man flight crew. It can also carry a survey crew of up to 11 men, depending on the sensors being used.

Sensors which may be carried include camera systems, a laser profiler, infrared systems, an imaging line scanner (RS–14 dual-channel scanner), passive microwave, active microwave (radar), and environmental systems.

Camera systems include two Wild-Heerbrugg RC–8 cameras, four Chicago Aerial KA62 multiband cameras, and a Flight Research model 207 (boresight) camera.

Infrared systems include a filter-wheel spectrometer, an infrared radiometer, and a precision radiation thermometer (PTR–5).

The passive microwave systems comprise a multifrequency microwave radiometer (MFMR) and a passive microwave imaging system (PMIS).

The active microwave (radar) system has as its components a 16.5-GHz side-looking airborne radar (SLAR) and two scatterometers in the 400-MHz and 13.3-GHz frequency ranges.

The environmental systems comprise a liquid water content indicator, a total air temperature indicator, and a dewpoint hygrometer.

Systems which support the aircraft and the operation of these sensor arrays include a radar altimeter (APN–159), a doppler radar, an inertial navigation system (LTN–51), a loran navigation system, an auxiliary data annotation system (ADAS), a 14-channel tape recorder (AR1600) and a four-channel strip chart recorder.

The ADAS provides information as to altitude, groundspeed, drift angle, pitch, roll, heading, and other such information needed to correlate the data acquired with time and geographic position.

The tape recorder provides a direct record with 1.5-MHz response at 152.4 cm/s, with signal conditioning for continuous bandwidth, proportional bandwidth, and pulse-code modulation.

NC–130B (NASA 929)—In September 1969, a Lockheed Hercules was obtained to provide the program with greater ranges, altitudes, and payloads. The NC–130B is a four-engine turboprop aircraft, with an operational ceiling of 9 km, an endurance of 8 hours at this altitude, and a range of 4000 km. True airspeeds range from 275 to 610 km/h. Three men make up the flight crew, and accommodations can be made for an eight-man survey crew, depending on the sensors being employed.

Sensor systems include cameras (two Wild-Heerbrugg RC–8's and six Hasselblad EL–500 multiband cameras), an infrared precision radiation thermometer (PRT–5), imaging line scanners (a 24-channel multispectral scanner and a Reconofax IV infrared scanner), a 13.3-GHz active microwave scatterometer, and environmental systems including a liquid water content indicator, a total air temperature indicator, and a dewpoint hygrometer.

Support systems include the radar altimeter (APN–159), the LTN–51 inertial navigation system, a closed-circuit television system, and a two-channel strip chart recorder. The ADAS and the AR1600 14-channel tape recorder are similar to those in the NP–3A aircraft.

RB–57F (AF13501)—An agreement with the U.S. Air Force permitted flight time aboard an Air Weather Service RB–57F reconnaissance aircraft for the high-altitude phase of the program which began in July 1969.

The RB–57F is equipped with two TF–33 turbofan engines plus two J–60 auxiliary engines. It can cruise at an operational altitude of from 12 to 18 km, with 5 hours' endurance over a range of 4000

km at a true airspeed of 740 km/h at maximum altitude. The craft carries a two-man crew consisting of the pilot and a systems operator/navigator.

Camera systems on board consist of two Wild-Heerbrugg RC–8 cameras, either a Zeiss RMK 30/23 or 15/23 camera or a Chicago Aerial KA50A camera, six Hasselblad EL–500 multiband cameras, and a Flight Research model 207 (boresight) camera.

Infrared systems include the filter-wheel spectrometer and the infrared radiometer.

The RS–7 infrared scanner provides an imaging line scanner to complete the sensor array.

Support systems on the RB–57F aircraft are identical to those on the NC–130B, less the strip chart recorder.

C–47—The C–47 aircraft operated by the Willow Run Laboratories of the University of Michigan serves as an aerial platform for the multispectral data collection system developed by the university under Government sponsorship. This system is composed of four detector assemblies, one installed at each end of two dual-channel scanners which provide calibrated radiation references through 18 multiband data channels in the 0.3-to-14.0-μm wavelength region.

The airborne sensor equipment is installed in two instrumentation wells in the bottom of the C–47 aircraft, housing the imaging equipment. The airborne system is operated by a crew of seven, including the pilot, copilot, and flight engineer. Data is collected at flight altitudes from 150 meters to 4.5 km above sea level.

At an altitude of 300 meters, spectral signatures of targets as small as approximately 3 meters in diameter can be registered quantitatively in 18 bands on magnetic tape. The quantitative measure of the signal level (radiance) in each band is established by interpolation between two known radiation inputs at the scanner aperture. The radiation inputs are common to data channels within a scanner and can be compared between scanners.

U–2—NASA is expanding its airborne research program by acquiring two U–2 aircraft on loan from the U.S. Air Force. The primary function of these high-altitude aircraft will be to provide ERTS simulation data. Other uses will be to collect underflight data over various test sites simultaneously with passes of the ERTS satellites and Skylab and to support Earth resources survey programs of other agencies.

The U–2 is a single-seat aircraft powered by a J–75 turbojet engine. It is capable of flying at an altitude of about 20 km at true airspeeds of 720 km/h and is thus ideally suited as a platform for remote sensing of large areas. For example, a single photograph from high altitude can encompass 130 square kilometers of the Earth's surface.

Initially, it is planned to fly the International Imaging Systems Mark I multispectral camera on these aircraft. Subsequently, cameras of the 70-mm film format with 45-mm-focal-length lens will be installed as the "workhorse" sensors to provide small-scale, multispectral, repetitive data for selected areas in the ERTS simulation program.

Figures 2 through 4 show the location of the sensors on three of the aircraft in the program. The ERTS simulation cameras in the U–2 will be located conventionally in the camera bay.

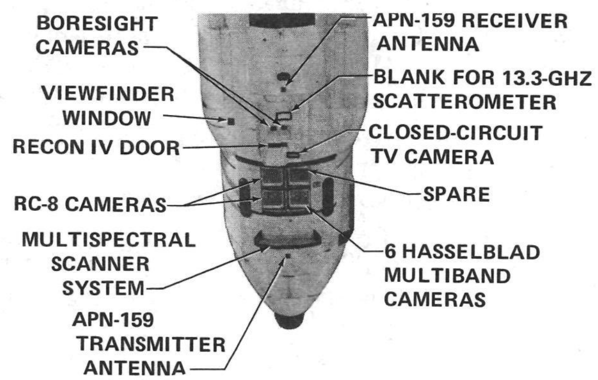

FIGURE 2. Bottom view of NC–130B.

AN INTEGRATED PROGRAM

The aircraft program has supported the basic and applied research which has been conducted by NASA and the cooperating agencies of the Government since 1965. The ERTS simulation to be performed by the U–2 aircraft involves the overflight of three different areas in the U.S. representing different resource management problem areas. Flights will be repeated each 18 days so that investigators studying these areas will have experience with data supplied by the multispectral cameras, which have the same frequency response and repetition rate as the ERTS television cameras.

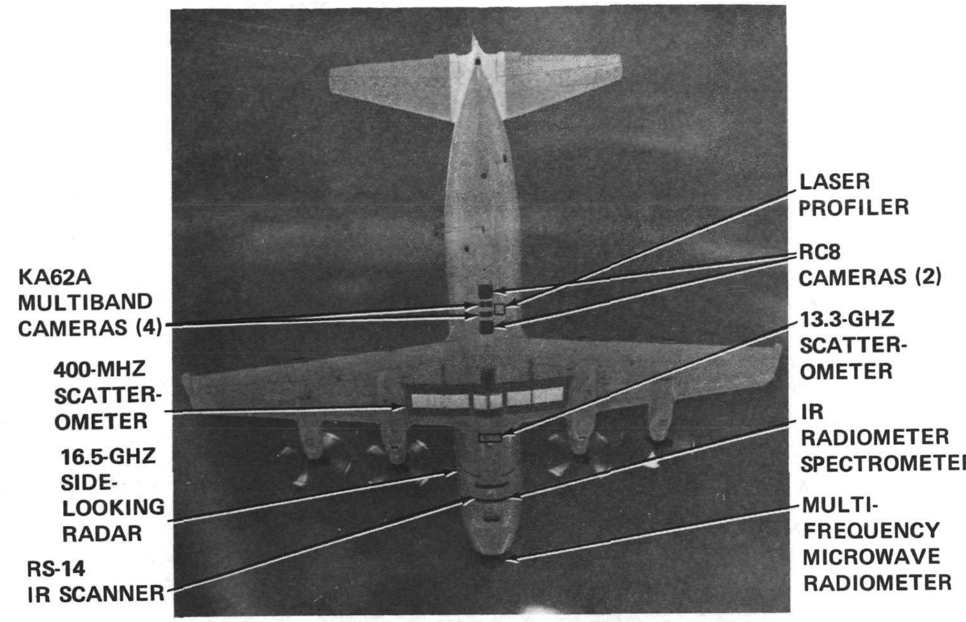

FIGURE 3. Bottom view of NP–3A.

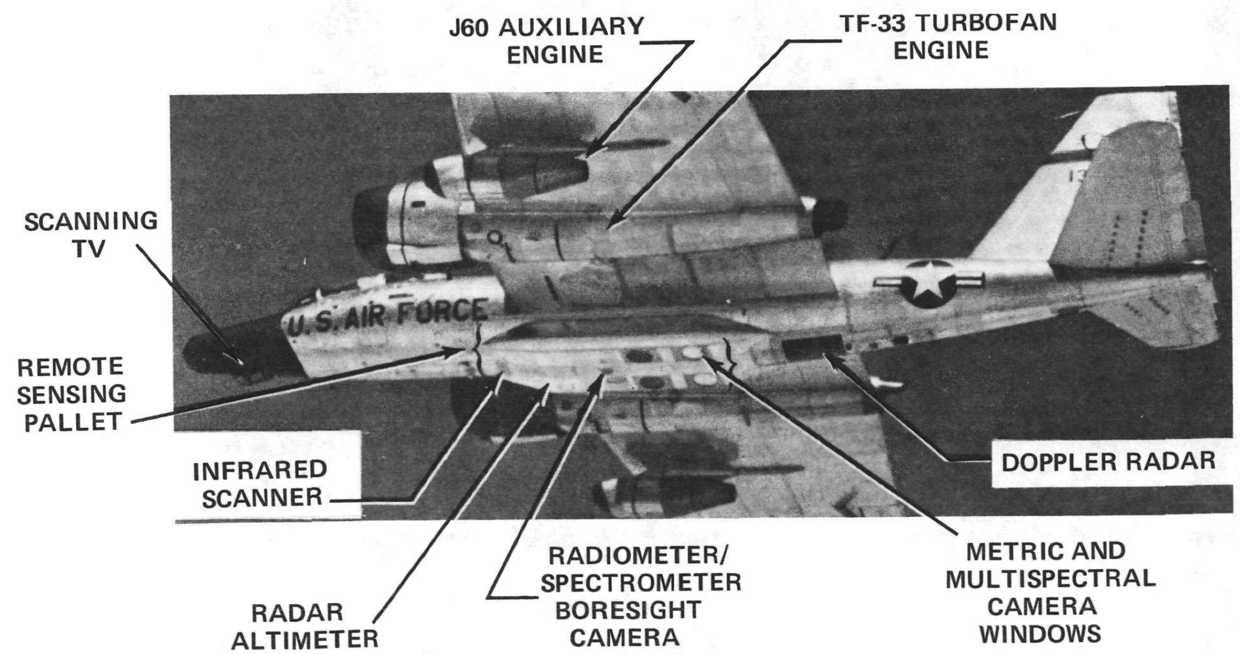

FIGURE 4. Bottom view of RB–57A.

When ERTS-A is launched, the aircraft in the program will by flying in support of the spacecraft experiments, many of which require multistage sampling, which is to be described later in the workshop. It is the opinion of the majority of the senior investigators in the Earth Resources Survey Program that there is a role for both aircraft and spacecraft in the program, and that the two systems should not be considered to be in competition, but as complementary parts of an integrated program.

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Systems Approach to the Use of Remote Sensing

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A tutorial discussion is presented of Earth resources information systems which utilize satellites as sensor platforms. It points out that information may be derived by sensing and analyzing the spectral, spatial, and temporal variations of electromagnetic fields emanating from the Earth's surface. After an overview of a system organization is presented, the two broad categories of system types are discussed: (1) systems in which high-quality imagery is essential and (2) systems that are more numerically oriented. Sensors are also discussed with this categorization of systems in mind.

The multispectral approach and pattern recognition are described as examples of data analysis procedures for numerically oriented systems. The steps necessary in using a pattern recognition scheme are described and illustrated with data obtained from Apollo 9. Both manual and machine-aided training techniques are described for the pattern recognition algorithm.

WHAT IS REMOTE SENSING?

Imagine that you are high above the surface of the Earth looking down on it and that you want to survey the Earth's surface in order to learn about its resources and thus to manage them better. How can this information be derived? What must the system to extract it look like?

The field of remote sensing provides some of the answers. Remote sensing is the science and art of acquiring information about material objects from measurements made at a distance, without coming into physical contact with the objects. In remote sensing, information may be transmitted to the observer either through force fields or electromagnetic fields, and in particular through the spectral, spatial, and temporal variations of these fields. Therefore, to derive information from these field variations, one must be able to measure the variations and relate these measurements to those of known objects or materials. If, for example, one desirës a map showing all of the water bodies of a certain region of the Earth, it is clear that one cannot sense the water directly from spacecraft altitudes, but only the manifestations of water that exist at that height. These manifestations, in the form of electromagnetic radiation, must therefore be measured and the measurements analyzed to determine which points on the Earth contain water and which do not.

Of the two types of fields mentioned above, electromagnetic fields provide perhaps the greatest potential. The remainder of these remarks will be confined to fields of this type. Figure 1 provides a review of the electromagnetic spectrum. The visible portion, extending from 0.4 to 0.7 μm, is the most familiar to us because it is this portion of the spectrum to which our eyes are sensitive. Sensors can be built, however, to cover a much broader range of wavelengths. The entire portion from 0.3 to 15 μm, referred to as the optical wavelength portion, is of particular interest. The optical wavelengths shorter than 0.4 μm are in the ultraviolet region. The portion with wavelengths longer than 0.7 μm is the infrared region, with the band from 0.7 to approximately 3 μm referred to as the reflective infrared and the region from 3 to 15 μm called the emissive or thermal infrared region. In this latter portion of the spectrum, energy is

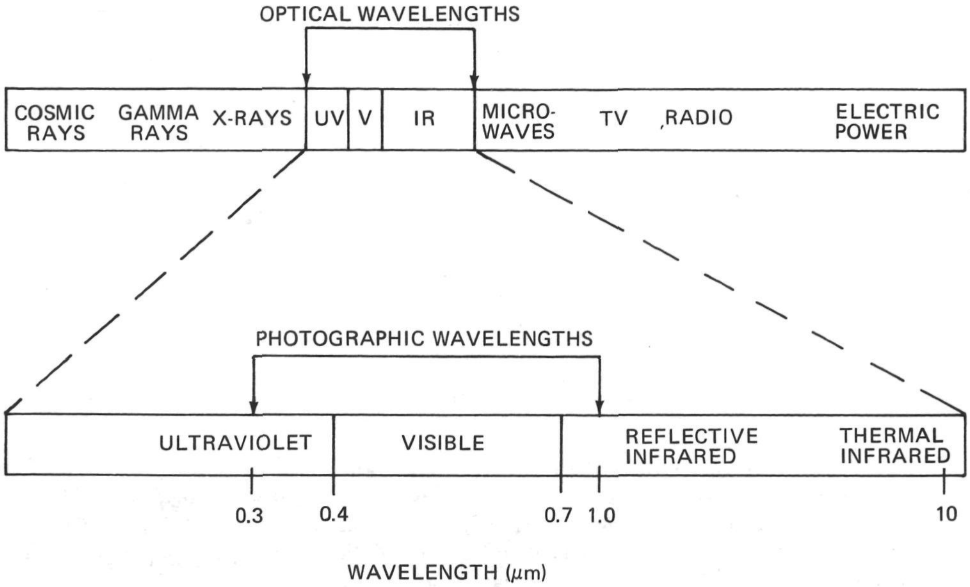

FIGURE 1. The electromagnetic spectrum.

emitted from a body as a result of its thermal activity, or heat, rather than being reflected from it.

In addition to the optical wavelengths, the microwave range is also useful in remote sensing. Preliminary results using both passive microwave and radar sensors indicate considerable promise for the microwave portion of the spectrum. For reasons of simplicity and in the interest of time, however, we shall limit our considerations in the remainder of this discussion to the optical portion of the spectrum.

Figure 2 is a diagram of the organization of an Earth survey system. It is necessary, of course, to have a sensor system viewing the portion of the Earth under consideration. There will necessarily be a certain amount of onboard data processing. This will perhaps include the merging of data from other sources, such as sensor calibration and data about where the sensor was pointed.

One must next transport the data back to Earth for further analysis and processing. This may be done through a telemetry system, as will be the case for the Earth Resource Technology Satellite (ERTS), or through physical package return, as will be used with Skylab. There is then usually a need for certain preprocessing of the data before the final processing with one or more of the data reduction algorithms. It is at this point in the system, when the data is reduced to information, that it is usually helpful to merge ancillary information, perhaps derived from sources on the surface of the Earth.

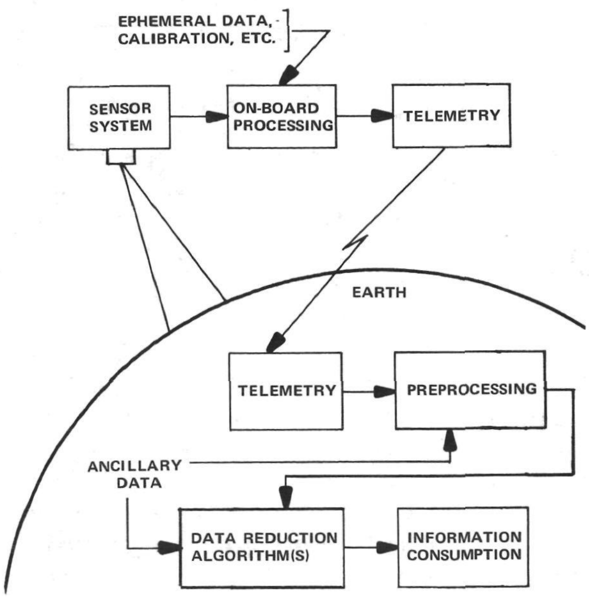

FIGURE 2. Block diagram of an Earth survey system.

An important part of the system which must not be overlooked is indicated by the last block in figure 2, that of information consumption, for there is no reason to go through the whole exercise if the information produced is not to be used. In the

case of an Earth resources information system, this last portion can prove to be the most challenging to design and organize, since many potential consumers of this information are not accustomed to receiving it from a space system and may indeed know very little about the information-providing capabilities.

to deal with these experimental variables in several ways. We shall touch briefly on this point later in the discussion.

Summarizing, then, it is possible to derive information about the Earth's surface and the condition of its resources by measuring the spectral, spatial, and temporal variations of the electromagnetic fields emanating from points of interest and then analyzing these measurements to relate them to specific classes of materials. To do so, however, requires an adequate understanding of the materials to be sensed and, to make the information useful, precise knowledge about how the information will be used and by whom.

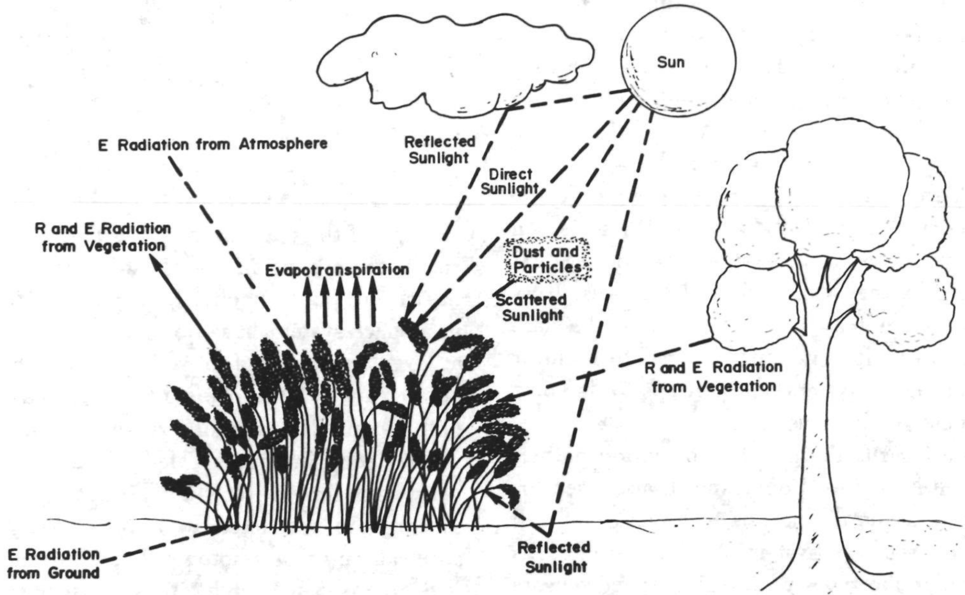

FIGURE 3. Reflected (R) and emitted (E) radiant energy exchange in a natural environment.

Before leaving the matter of the organization of an information system, the necessity of having a thorough understanding of the portion of the system preceding the sensor must be pointed out. Figure 3 shows a simplified version of the energy exchange in a natural environment. It is possible, of course, to detect the presence of vegetation on the Earth's surface by measuring the reflected and emitted radiation emanating from the vegetation. One must understand, however, that there are many experimental variables active. For example, the Sun provides a constant source of illumination from above the atmosphere, but the amount of radiation that is reflected from the Earth's surface depends upon the condition of the atmosphere, the existence of surrounding objects, and the angle between the Sun and the Earth's surface, as well as the angle between the Earth's surface and the point of observation. Even more important is the variation which will exist in the vegetation itself. It is possible

THE DUALITY OF SYSTEM TYPES

When we consider the state of the art of remote sensing today, a duality of system types becomes readily apparent. Development in the field has had two major stems since it originated from two somewhat different types of technology. These two types of systems will be referred to here as (1) image oriented and (2) numerically oriented.

An example of an image-oriented system might be simply an aerial camera and a photointerpreter. The photographic film is used to measure the spatial variations of the electromagnetic fields, and the

photointerpreter relates these variations to specific classes of surface cover. Numerically oriented systems, on the other hand, tend to involve computers for data analysis. Although the photointerpreter and the computer, respectively, tend to be typical of the two types of systems, it would be an oversimplification and indeed incorrect to say that they are uniquely related to these system types. This becomes clearer upon further examination.

Figure 4 compares the organization of the two system types. Both types of system need a sensor and some preprocessing. The distinction between the types can perhaps be brought out most clearly by noting the location of the FORM IMAGE block in the two diagrams. In the image-oriented type, it is in line with the data stream and must precede the ANALYSIS block. Numerically oriented systems, on the other hand, need not necessarily contain a FORM IMAGE block. If they do, and in Earth resources they usually do, it may be at the side of the data stream, as shown. It may thus be used to monitor the operation of the system and perhaps to do some special-purpose analysis as needed.

In considering the design of information gathering systems, it is of great importance that the sensor, as well as the means of analysis to be used, be well mated to the type of system orientation. Let us briefly consider the types of imaging space sensors available.

Perhaps the single most distinguishing characteristic of Earth resources information systems is that a very large amount of data can be, and indeed must be, gathered in order to derive the desired information. Since an image is a very efficient way to communicate large quantities of data to man, we shall arbitrarily restrict this discussion to sensors which are capable of creating images. Imaging sensors can be broadly classified as photographic, television, and scanner types.

The great advantage of photography is the high spatial resolution that can be achieved; but to maintain this high resolution, data retrieval by physical package return is required. Also, photography as a sensor is useful only in the visible portion and a small part of the reflective infrared portion of the spectrum.

Television has the advantage that the signal occurs in electrical form and is therefore immediately ready to be transmitted back to the Earth.

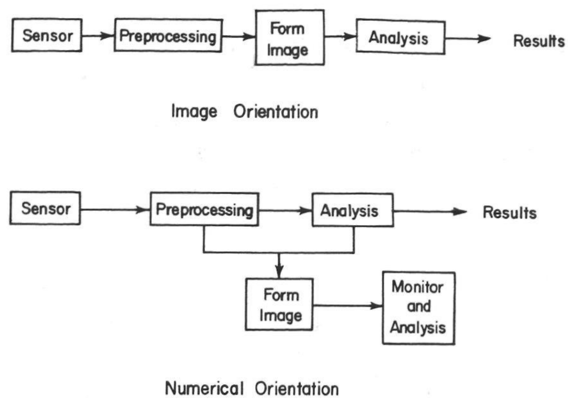

FIGURE 4. Organization of image-oriented and numerically oriented systems.

Storage of the data, however, is not inherently present in the system in a permanent form, as it is in the case of photography. In using a television sensor in a space system, it is not necessary to carry along a large quantity of a storage medium (such as photographic film). This advantage may be viewed both as an advantage of size and weight and as one of efficiency in that a satellite may be operated a very long time with a single servicing. Television sensors are restricted to approximately the same spectral range as photography, however.

Scanners can be built to operate over the entire optical wavelength range. They can also provide a greater photometric dynamic range. In order to achieve these advantages, however, they tend to be more mechanically complex.

It is important to realize that the advantages and disadvantages mentioned here must be considered only as examples, since the advantages and disadvantages in any specific instance will depend upon the precise details of the system. General statements are also difficult to make as to the type of sensors that will be best for image-oriented and numerically oriented systems. There is a clear tendency to favor photography for image-oriented systems because of its high spatial resolution capability, while multiband scanners tend to be favored for numerically oriented systems because they make available greater spectral and dynamic ranges.

The technology for pictorially oriented systems is relatively well developed. Sensors best suited to this type of system have been in use for some time, as have appropriate analysis techniques. This type

of system also has the advantage of being easily acceptable to the layman or neophyte. This is an important advantage in the Earth resources field, since many new data users are expected. Similarly, it is well suited for producing subjective information and is especially well suited to circumstances where the classes into which the data is to be analyzed cannot be precisely established beforehand. Thus man, with his superior intelligence, can be deeply involved in the analysis activity. Pictorially oriented systems also can be relatively simple and inexpensive. On the other hand, it is difficult to use them for large-scale surveys over very large areas involving very large amounts of data.

In the case of numerically oriented systems, the technology is much newer and not nearly so well developed, though very rapid progress is being made. Because the various steps involved tend to be more abstract, they tend to be less readily understandable to the layman. This type of system is best suited for producing objective information, and large-scale surveys covering large areas are certainly possible. Numerically oriented systems tend to be generally more complex, however.

In summary to this point, the state of the art is such that there are two general types of systems. This duality exists primarily for historical reasons and because of differences of the points from which technology development began. One type is based on imagery, and therefore a key goal of an intermediate portion of the system is the generation of high-quality imagery. In the other case, imagery is less important and indeed may not be necessary at all. It is not appropriate to view these two types of systems as being in competition with one another, since they have different capabilities and are useful in different circumstances. These two stems of technology are approaching one another so that the differences between them are becoming less distinct.

We will proceed now to a further consideration of numerically oriented systems, since this type may be less familiar. In particular, we shall examine a type of data analysis that is useful in this type of system.

THE MULTISPECTRAL APPROACH AND PATTERN RECOGNITION

In recent years considerable effort has been devoted to what is referred to as the multispectral

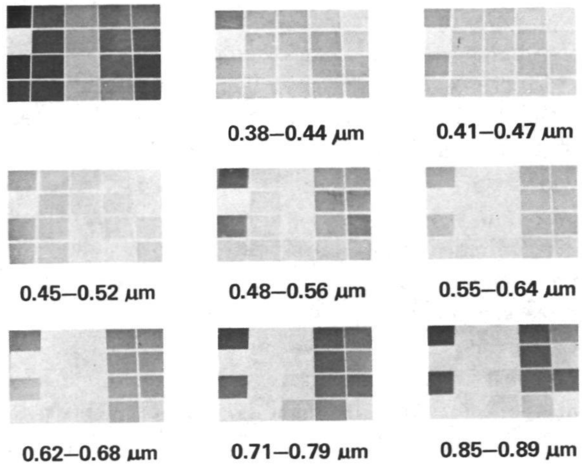

FIGURE 5. Multispectral photography of color cards.

approach for data analysis. An initial understanding of what is meant by the term multispectral approach may be obtained by considering figure 5. In the upper left is a reproduction of a conventional color photograph of a set of color cards. The remainder of the figure shows photographs of the same color cards taken with black-and-white film and several different filters. The passband of each filter is indicated beneath the particular color card set. For example, in the 0.62-to-0.68-µm band, which is in the red portion of the visible spectrum, the red cards appear white in the black-and-white photo, indicating a high response, or a large amount of red light energy being reflected from these cards. The multispectral approach in this case amounts to identifying any color by noting the set of gray-scale

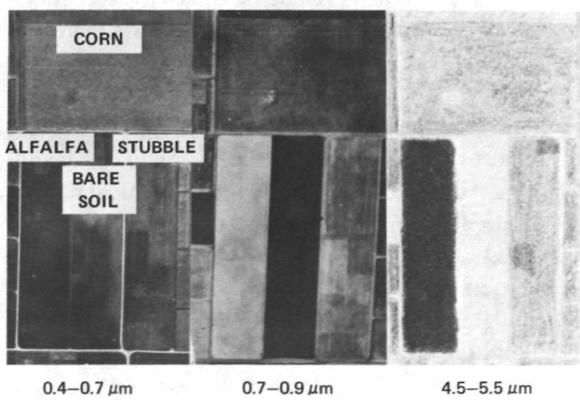

FIGURE 6. Multispectral response of corn, alfalfa, stubble, and bare soil.

values produced on the black-and-white photographs for that particular color rectangle.

Figure 6 shows images of an agricultural scene taken in three different portions of the spectrum. Note that in the three bands alfalfa has responses which are dark, light, dark, respectively, whereas bare soil is gray, dark, white. Thus alfalfa can be discriminated from bare soil by identifying the fields which are dark, light, dark in order in these three spectral bands.

One may initially think of the multispectral approach as one in which a very quantitative measure of the color of a material is used to identify it. Color, however, is a term usually related to the response of the human eye. The terminology of spectroscopy is more precise and therefore more useful in understanding the multispectral approach, which is applicable beyond the visible region.

In order to understand this approach and to see how a numerically oriented system may be based upon it, consider figure 7. Shown at the top is a graph of relative response (reflectance) as a function of wavelength for three types of Earth-surface cover material: vegetation, soil, and water. Let two wavelengths marked λ_1 and λ_2 be selected. Shown in the lower part of this figure are response data for these three materials at these two wavelengths, plotted with respect to one another. For example, in the upper graph soil has the largest response at wavelength λ_1; this manifests itself in the lower plot in that soil has the largest abscissa value (the greatest displacement to the right).

It is readily apparent that two materials whose response as a function of wavelength are different will lie in different portions of the two-dimensional space.* When this occurs, one speaks of the materials involved as having unique spectral signatures. This concept will be pursued further presently; at this point it is important to recognize that the concept of a spectral signature is a relative one. One cannot know that vegetation has a unique spectral signature, for example, until one sees the plots resulting from the spectral response of other materials within the scene to be analyzed. Note also that a larger number of bands can be used. The response at λ_3 could be used and the data plotted in three dimensions. Four or more dimensions indeed have meaning and

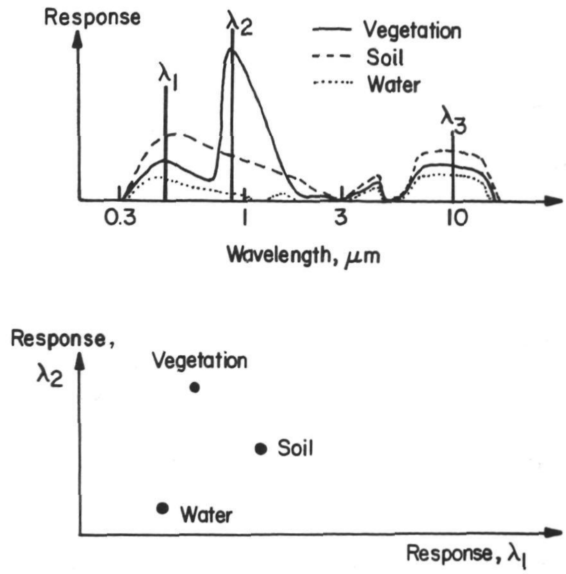

FIGURE 7. Spectral data in two-dimensional feature space.

utility, even though an actual plot of the data is not possible.

So far no spatial or temporal information has been involved, only spectral. Temporal information can be utilized in several ways. Time is always a parameter of the spectral response of surface materials. As an example, consider the problem of discriminating between soybeans and corn. Under cultivation, these two plants have approximately 140-day growing cycles. Figure 8 illustrates what the two-dimensional response plot might be for fields of these two plants with time as a parameter. Upon planting and for some period thereafter, fields of soybeans and corn would merely appear to be bare soil from an observation platform above them. Eventually though, both plants would emerge from the soil, develop a canopy of green vegetation, and diminish. As viewed from above, the fields of soybeans and corn would, in fact, always be mixtures of green vegetation and soil. In addition to the vegetation of the two plants having a slightly different response as a function of wavelength, the growing cycles and plant geometries are different. Thus, the mixture parameters permit an even more obvious difference between the two plants than the spectral response difference of the plant leaves themselves. This is shown in figure 8 by the rather large difference between the two crops at 30 days from planting date (partial canopy) as compared to

* This space is referred to as feature space.

75 days (full canopy). Thus, one way in which temporal information is used is simply in determining the optimum time at which to conduct a survey of given materials.

A second use of temporal information is perhaps less obvious. Consider the situation of figure 8 at the 75-day and 100-day points. In this case the separation of the two materials is relatively slight. However, if this data is replotted in four-dimensional space with λ_1 and λ_2 at 75 days as dimensions one and two and λ_1 and λ_2 at 100 days as dimensions three and four, the small separations at the two times can often be made to augment one another.

A third use of temporal information is simply that of change detection. In many Earth resources problems it is necessary to have an accurate historical record of the changes taking place in a scene as a function of time.

Let us move now to consider how a procedure can be devised for analyzing multispectral data. In the process, one further facet of the multispectral approach must be taken into account. The radiation from all soybean fields will not have precisely the same spectral response, since all will not have had the same planting date, soil preparation, moisture conditions, and so on. Indeed, response variation within a class may be expected of any Earth-surface cover. The extent of response differences of this type certainly has an effect upon the existence of a spectral signature, i.e., the degree of separability of one material from another. Consider, for example, a scene composed of soybean, corn, and wheat fields. If five samples of each material are drawn, the two-dimensional response patterns might be as shown in figure 9, indicating some variability exists within the three classes. Suppose now an unknown point is drawn from the scene and plotted, as indicated by the point marked U.

The design of an analysis system in this case comes down to partitioning this two-dimensional feature space so that each such possible unknown point is uniquely associated with one of the classes. The engineering and statistical literature of the world abounds with algorithms or procedures by which this can be done. One very simple one is shown in figure 10. In this case the conditional centroid or center point of each class is first determined. Next the locus of points equidistant from these three centroids is plotted, resulting in three straight line segments as shown.* These lines form,

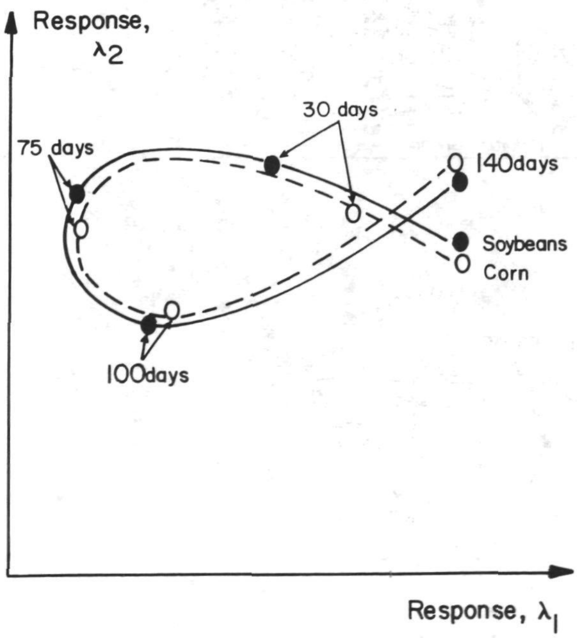

FIGURE 8. Temporal change in two-dimensional feature space.

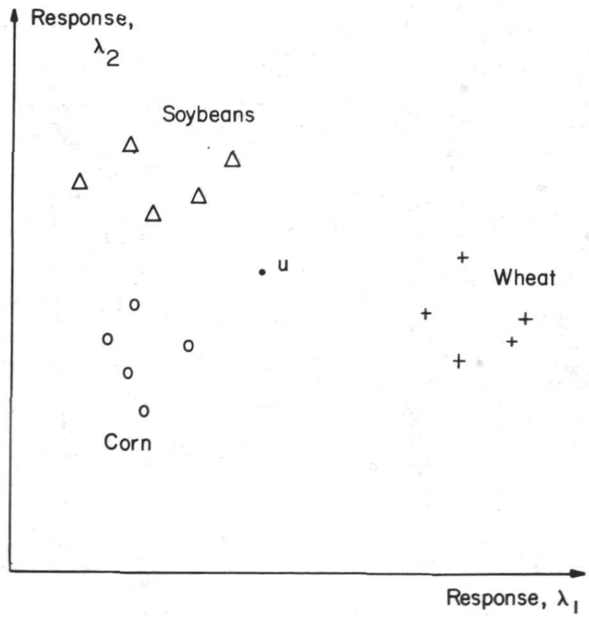

FIGURE 9. Samples in two-dimensional feature space.

* When more than two dimensions (spectral bands) are being used, this locus becomes a surface rather than a line.

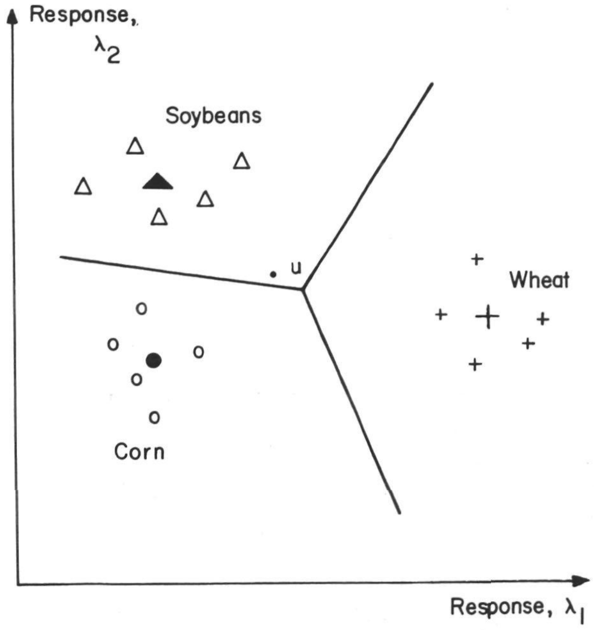

FIGURE 10. Minimum distance to means classification.

in effect, decision boundaries. In this example the unknown point U would be associated with the class soybeans as a result of the location of it with respect to the decison boundaries.

This technique of analysis is referred to as pattern recognition, and there are many more sophisticated procedures resulting in both linear and nonlinear decision boundaries. The procedure of using a few initial samples to determine the decision boundaries is common to a large number of them. The initial samples are referred to as training samples, and the general class of classifiers in which training samples are used in this way are referred to as supervised classifiers.

Up to this point the implication has been that photography or multispectral photography is the sensor to be used in generating data for this type of analysis procedure. While indeed this data source can be used, a perhaps more appropriate one is a device known as a multispectral scanner. Figure 11 diagrams such a device as it might be used in an aircraft.

Basically the device consists of a multiband spectrometer whose instantaneous field of view is

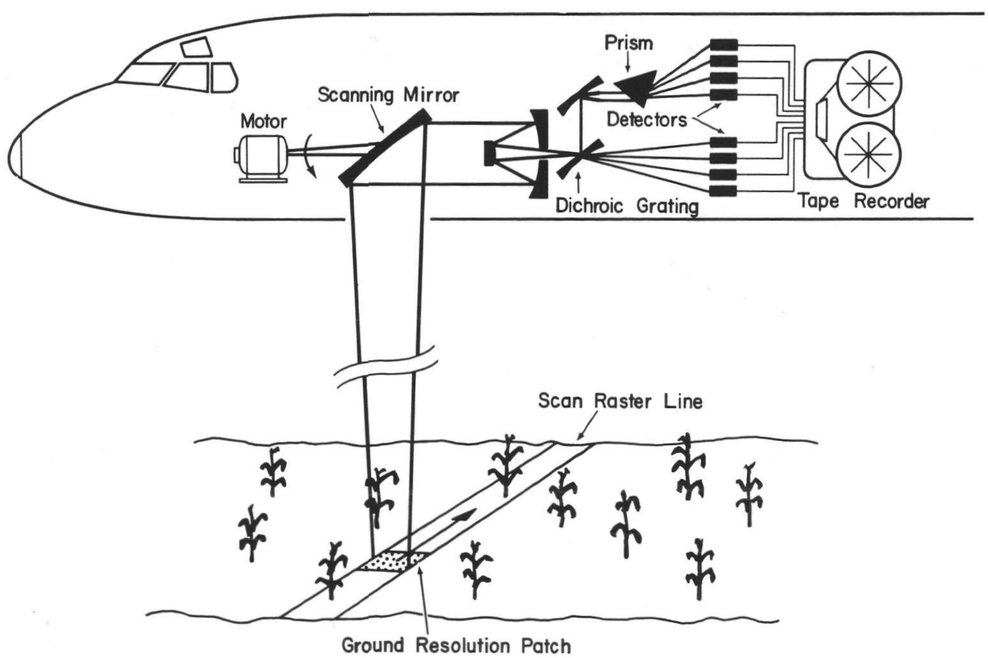

FIGURE 11. Schematic diagram of an airborne multispectral scanner.

scanned across the scene. The scanning in this case is accomplished by a motor-driven scanning mirror. At a given instant the device is gathering energy from a single resolution element. The energy from this element passes through appropriate optics and may, in the case of the visible portion of the spectrum, be directed through a prism. The prism spreads out the energy according to the portion of the spectrum; detectors are located at the output of the prism. The output of the detectors can then be recorded on magnetic tape or transmitted directly to the ground. Gratings are commonly used as dispersive devices for the infrared portion of the spectrum.

A most important property of this type of system is *that all energy from a given scene element in all* parts of a spectrum passes through the same optical aperture. Thus, by simultaneously sampling the output of all detectors, one has, in effect, determined the response as a function of wavelength in each spectral band for the scene element in view at that instant.

Of course, the scanning mirror causes the scene to be scanned across the field of view at right angles to the direction of platform motion, and the motion of the platform (aircraft) provides the appropriate motion in the other dimension so that in time every element in the scene has been in the instantaneous field of view of the instrument.

As an example of the use of this type of sensor and analysis procedure, results of the analysis of a flightline will be presented in brief form. The particular example involves the classification of a 1.6-kilometer strip into classes of agricultural significance. Four-dimensional data (four spectral bands) were used for the classification. The data are shown in figure 12 along with a conventional panchromatic airphoto of the scene on which the correct classification of each field has been indicated. The symbols on the airphoto represent the following classes: S, soybeans; C, corn; O, oats; W, wheat; A, alfalfa; T, timothy; RC red clover; R, rye; Sudan, sudan grass; P, pasture; DA, diverted acres; and H, hay.

Figure 13 shows the results of the classification. Two simple classes are shown. All points of the scene classified as row crops (either corn or soybeans) are indicated in the center of the figure. On the right are indicated all points classified as cereal grains (either wheat or oats).

A quantitative evaluation of the accuracy was conducted by designating for tabulation the correct class of a large number of fields in the flightline. The result of this tabulation is presented in figure 14, which shows that all results for all classes are more than 80-percent correct.

The same procedures using aircraft data have been utilized for a wide number of classification tasks in addition to crop species identification. Some of these are: tests of agricultural and engineering soil; geologic feature mapping; water quality mapping and mensuration using both reflective and emissive spectra; forest cover identification and tree species delineation; and delineation into geographic and land use mapping categories.

SOME PROCEDURAL DETAILS IN THE USE OF PATTERN RECOGNITION

With the basic concept of pattern recognition in mind, it is possible to proceed to some further details on how it may be applied. One of the more important of these details is the definition of the classes into which the data are to be categorized.

There are two conditions that a class must meet in order to be useful: The class must be *separable* from all others, and it must be of *informational value*. For example, it does no good to define a class called iron ore deposits if the spectral response which iron ore provides is not sufficiently distinct from all other Earth-surface materials over which data are to be gathered. On the other hand, if no one is interested in locating the iron ore deposits within the region to be surveyed, there is no reason to define such a class. We shall see presently that one may name classes of informational value and then check their separability, or vice versa.

A second matter is determining the point at which a class actually becomes defined. In an agricultural survey, simply naming a class "soybeans" does not define it precisely enough. For example, what percent ground cover is required before a given resolution element should have its classification changed from bare soil to soybeans? What percent of a resolution element may be covered with weeds and so on? The fact is that the class becomes precisely defined only by the training samples to be used for it. Thus, an important step in the procedure is the selection of training samples which are sufficiently typical of the whole class in question.

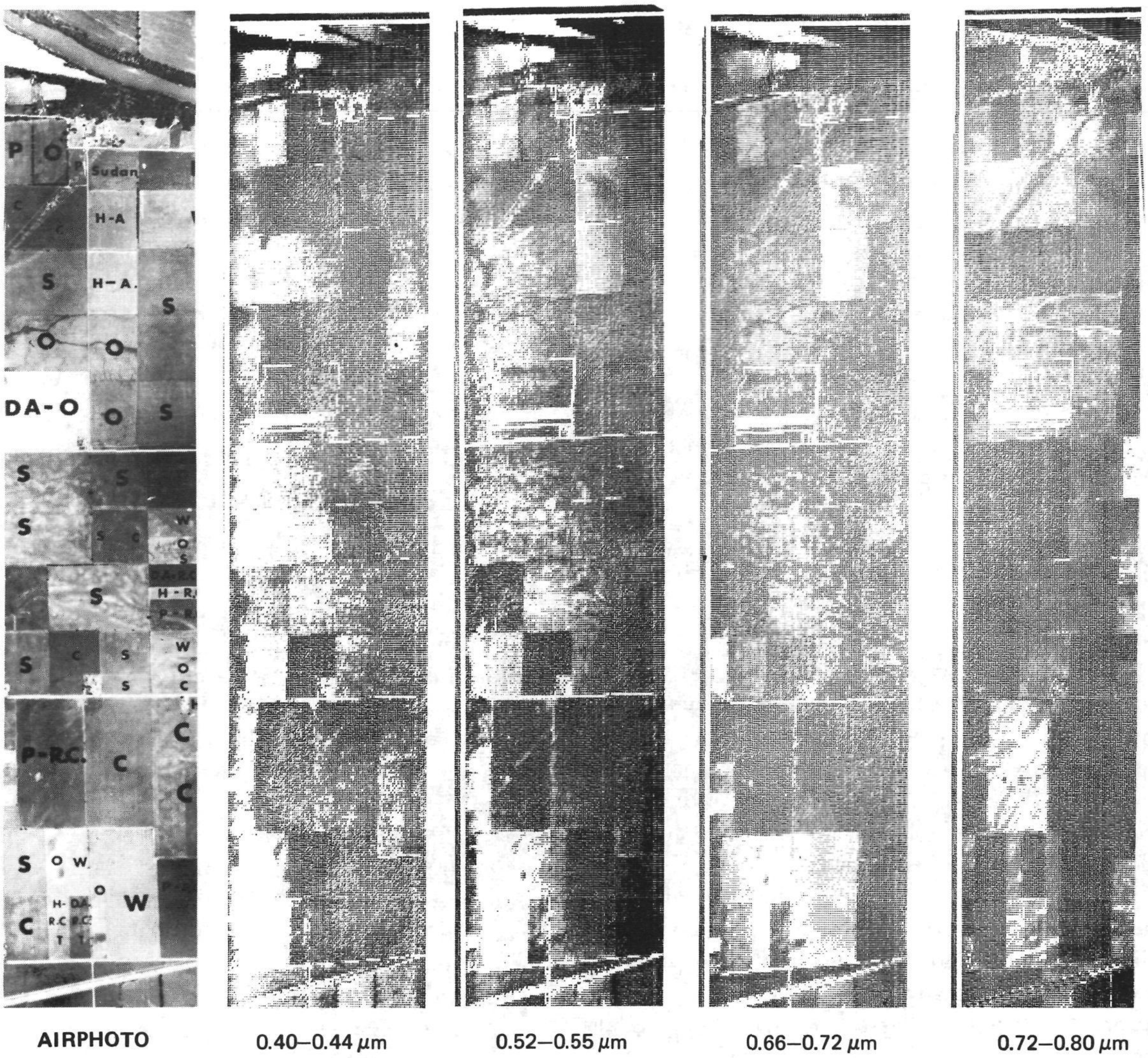

FIGURE 12. Data collected in four wavelengths, compared to panchromatic photoimage.

One must also recognize that the definition of a class is always a relative matter. That is, it is relative to the other classes used in the same classification. The effect of the decision boundaries is to divide up the feature space (figure 9) into non-overlapping regions depending on the relative location of the class training sets relative to one another.

It should also be noted, however, that as a result, every point in the space automatically becomes associated with one of the named classes. It is therefore necessary that the list of classes be exhaustive so that there is a logical class to which every point in the scene to be analyzed may be assigned.

As a result of these factors, it is apparent that the selection of training samples is especially important. There are two approaches to obtaining training data; we shall refer to them here as the signature bank approach and the extrapolation mode.

Using the signature bank approach, the researcher first decides on a list of appropriate classes and then draws from a signature bank previously collected data on the classes of material identical to those selected. This approach has a considerable amount of aesthetic appeal. Presumably one could accumulate a very large bank of data from typical

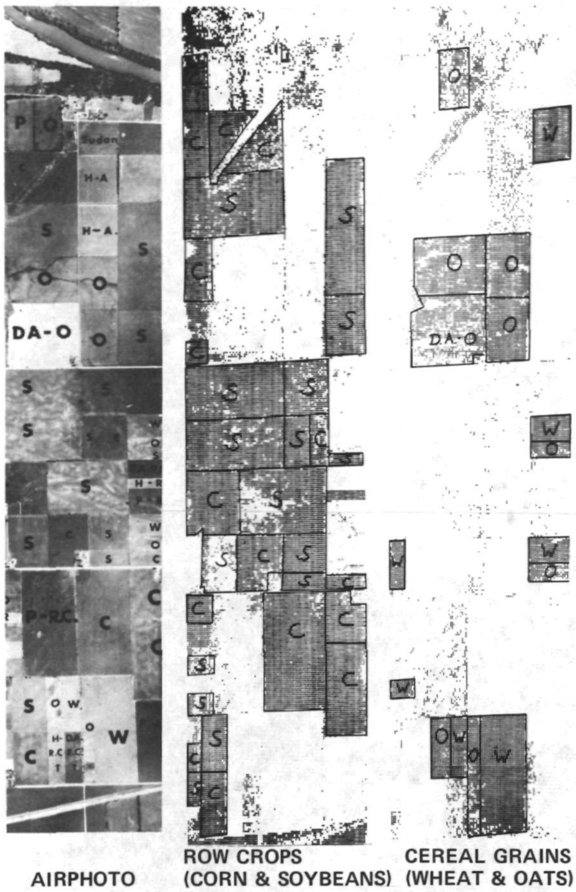

FIGURE 13. Spectral pattern recognition of row crops and cereal grains.

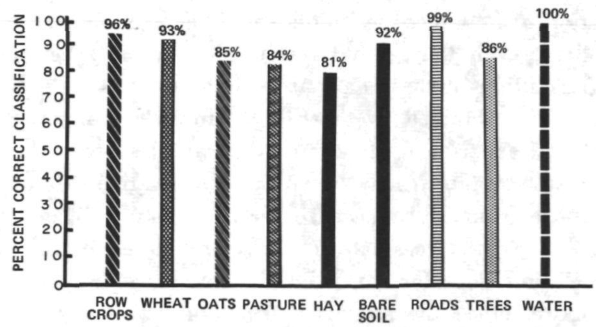

FIGURE 14. Classification results for test samples.

classes and thereafter always have training data available for any situation without further effort.

However, such an approach would place stringent constraints on the sensor system, since absolute measurements of scene radiance would be necessary if they are to be referenced to a future data-gathering mission. Furthermore, the extent to which detailed and sophisticated classes could be utilized would be limited by the ability to determine and adjust for the instantaneous values of all the other experimental parameters, such as the condition of the atmosphere, the Sun and view angles, possible seasonal variations in the vegetation, the natural statistical distribution of the data for various classes, etc. In short, while such a procedure is possible, it results in more stringent requirements on the sensor system and requires considerable data preprocessing in order to achieve this maximum utility. Alternatively, it would have to be restricted to cases in which only relatively simple classes were necessary.

The extrapolation mode has somewhat different characteristics. In this method training data for each of the classes are obtained by locating within the data to be analyzed specific examples of each of the classes to be utilized. The classification procedure, therefore, amounts to an extrapolation from points of known classification within the scene to the remaining portions of the data. This approach has the advantage of requiring less exactness in the calibration capability of the sensor system and in the knowledge of the other experimental variables, since only variation of these factors within the data-gathering mission, and not those from mission to mission, must be accounted for. On the other hand, it has the disadvantage of requiring some knowledge about the scene to be analyzed before the analysis can proceed. In the case of populated or accessible areas, this knowledge usually comes from ground observations. In the case of inaccessible areas as well as accessible and/or populated ones, it could perhaps also come from a very limited, low-altitude aircraft mission. The relative cost of this additional information often turns out to be low. The extrapolation mode was used in both the preceding example and the one to follow.

To illustrate these details and procedures, an example follows in which a pattern-recognition scheme was trained and then used to classify a relatively large amount of data. Data for this experiment were collected aboard the Apollo 9 space vehicle as a part of an experiment known as SO65. This example was selected because, in addition to illustrating the steps described above, it provides the first indica-

tion of how these techniques may perform on space data. Both the ground resolution and the spectral resolution of these data are similar to those which will be obtained by the ERTS. However, since the S065 experiment involved photographic sensors, the results obtained may be on the conservative side of those from ERTS because, as previously indicated, photography does not ordinarily provide the optimal type of data for this analysis procedure. Furthermore, since the sensors were photographic, some preliminary processing steps to prepare the data for analysis were necessary. These steps involved first scanning the photography (on a rotating-drum microdensitracer) to convert it to digital form, then bringing the images gathered over the same scene in the different spectral bands into spatial alinement with one another. These steps are not typical and are beyond the scope of the discussion at hand. We will proceed from the point at which the preprocessing steps provided four-dimensional data for analysis. The four spectral bands involved were 0.47 to 0.61 μm, 0.59 to 0.715 μm, 0.68 to 0.89 μm, and 0.51 to 0.89 μm. These bands were determined by the film and filter combinations used on the four cameras.

Figure 15 shows a color infrared version of the particular frame used, a portion of Southern California, Arizona, and Northern Mexico. In the lower left of the frame is the Imperial Valley, an irrigated area of very great importance agriculturally. Also shown in the figure is a computer-generated gray scale printout of one band of the data. The scene covers about 26 000 square kilometers and contains about five million points.

In order to test the separability of various classes, two analysis tasks were carried out. The first, involving agricultural classes, was carried out in the area designated by the small rectangle in the lower left of the printout. Figure 16 shows a high-resolution printout of this same area. The individual fields of the scene are clearly evident in this printout. To begin with, some relatively simple classes were defined. These were green vegetation, bare soil, water, and salt flats. Figure 17 shows the result of classifying the data into these categories. The accuracy of this classification was judged to be very high, and as a result it was decided to attempt a classification with more detailed categories. The result of this classification is shown in figure 18.

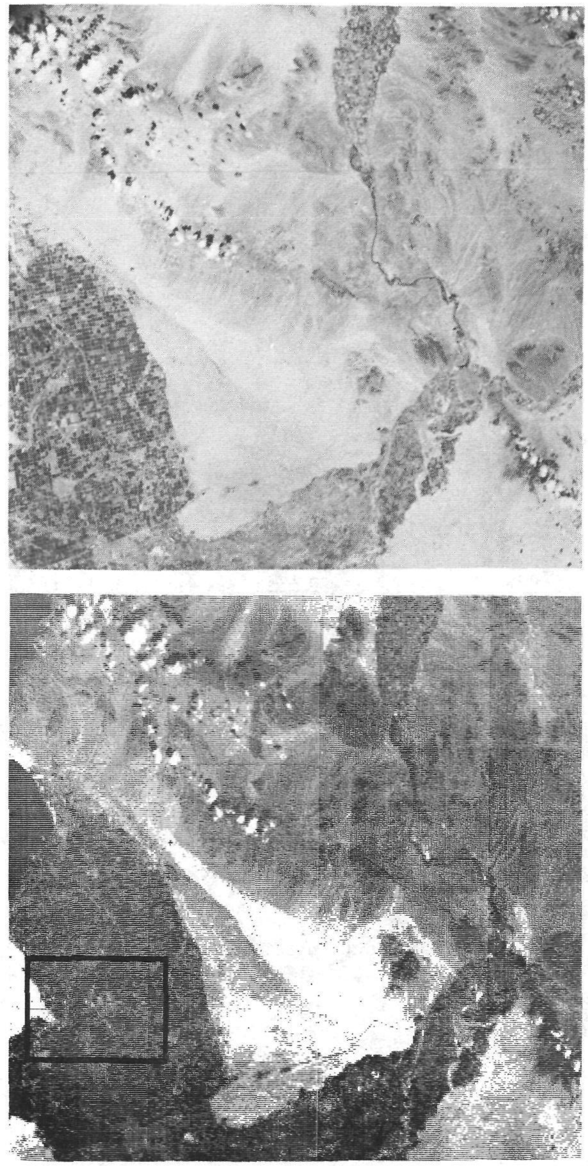

FIGURE 15. Color infrared photo from Apollo 9 and gray-scale panchromatic computer printout of Imperial Valley area in California. Visible green is represented by blue dye, visible red appears green, and infrared appears red.

It is seen that the classes used were barley, alfalfa, sugar beets, bare soil, salt flat, and water. A quantitative assessment of the accuracy in this case indicated an average accuracy of approximately 70 percent.

The second analysis task carried out on this data set was done over the whole frame. Classes of geologic interest were defined in this case, and an at-

FIGURE 16. High-resolution printout of a section of digitized image shown in figure 15.

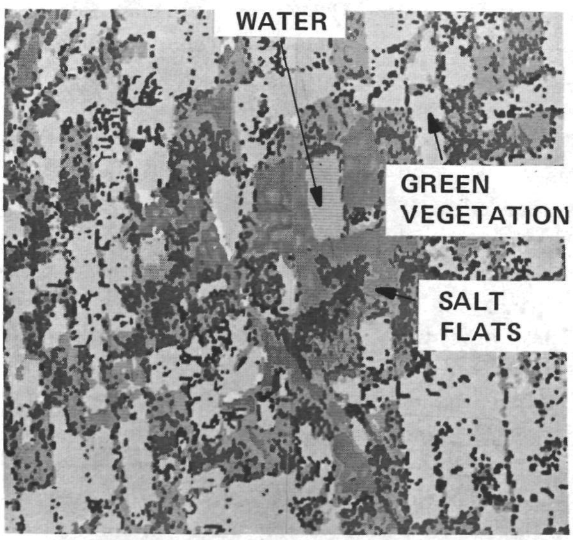

FIGURE 17. Classification of Apollo 9 data into green vegetation, salt flats, water, and bare soil classes. (Bare soil is represented by all colors other than those identified.)

FIGURE 18. Results of classification of alfalfa, barley, sugar beets, bare soil, salt flats, and water.

tempt was made to achieve what amounts to a geologic map of the area. The result of this classification is shown in figure 19. Some but not all of the classes used are indicated at the bottom of this figure. The results of this classification were compared with existing geologic maps of the area by a professional geologist, and again the results were judged to be highly satisfactory.

With an overview of the experiment and the results achieved in mind, let us now examine the procedures used to obtain the results. In the case of an agricultural problem, the classes of interest usually exist in well defined fields. It is therefore relatively easy to locate sample fields of each class from which to draw training samples. In this case, ground observations from a relatively small region on the ground can be used to derive a sufficient

FIGURE 19. Apollo 9 computer map of Imperial Valley region.

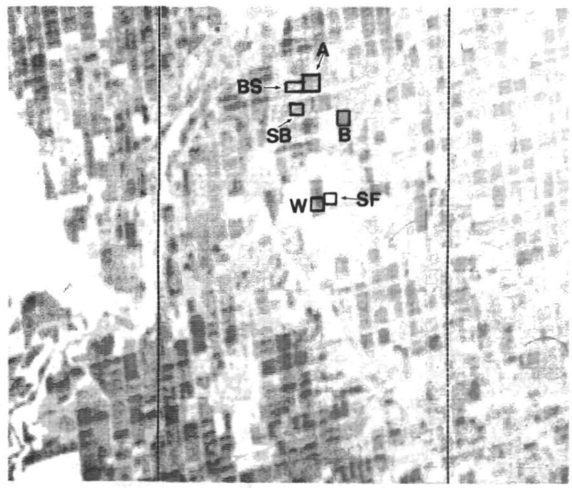

FIGURE 20. High-resolution printout with training fields.

number of training samples for each class. The number of training samples necessary for each class depends upon the number of spectral bands to be used among other things. But generally no more than a few hundred are required, fewer in simpler situations. Figure 20 depicts a typical situation for this type of classification. The fields outlined here are a typical set of training fields for such a classification task.

The classification of a natural area presents a slightly different situation, however. In this case it may be more difficult to locate training samples manually because boundaries between different materials will be more difficult to locate. Over the last year or two, research has been directed toward devising some machine-aided procedures for deriving training samples in this circumstance. One such procedure involves the use of a type of classifier that does not employ training samples and is therefore referred to as an nonsupervised classifier. The basic idea behind nonsupervised classifiers becomes apparent by considering the next several figures.

Assume that you have some two-dimensional data as shown in figure 21. Assume also that you know there are three classes of material represented by these data, but the correct association of the individual points with the three classes is unknown. The approach is to assume initially that the three classes are separable and check this hypothesis subsequently.

There are algorithms available that will automatically associate a group of such points with an arbitrary number of mode centers or cluster points. These procedures, known as clustering techniques, can be used to so divide the data, and the result of applying such a procedure might be as shown in figure 22. There remains, then, the matter of checking to be sure that the points assigned to a single cluster all belonged to the same class of material. In passing it is worth noting a comparison between supervised and nonsupervised classifiers. In the supervised case, one generally names classes of informational value and then checks to see if the classes are separable. The reverse is the case in the nonsupervised scheme. One separates the data and then checks to see if the resulting clusters are indeed associated with the classes of informational value.

Figure 23 shows the result of applying such a clustering technique to some multispectral data. The algorithm was instructed to form five cluster points.

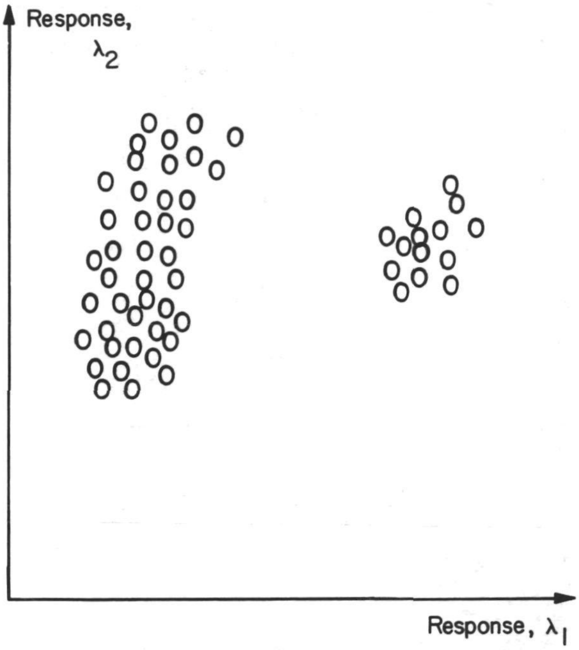

FIGURE 21. Samples of three classes in two-dimensional feature space.

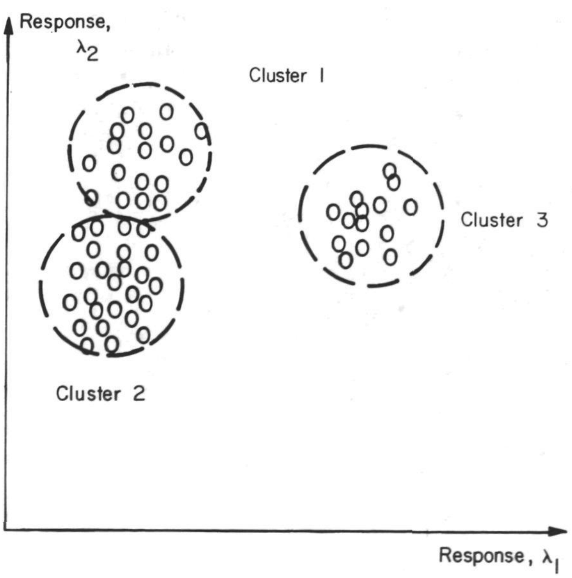

FIGURE 22. Clustering of samples in two-dimensional feature space.

Comparison of the clustering results with the data in image form shows that the clusters indeed were associated with individual fields. Cluster four, for example, was associated with fields in the upper left and and lower right, clusters two and three with the field in the lower left, and so on. Such a technique is used to speed the training phase of the classifier by aiding the human operator in obtaining points grouped according to class; the statistics of each cluster point can be immediately computed from the clustered results so that decision boundaries are located. The operator is thus relieved of the necessity of locating and separating individual fields for training each class.

The value of such a procedure is even greater in cases where the boundary between classes is not so distinct in the data. Figure 24 shows the result of clustering data for a soils mapping classification. Here it would be more difficult to select samples associated with specific soil types. As a result of the clustering, the operator has only to associate the soil type with each cluster point, and training samples are immediately available for further processing.

It was this latter procedure that was used in deriving training for the geologic map in the Apollo 9 data. Figure 25 shows the outline of cluster plots from which training was derived. In this case it was necessary only to mark regions containing at least the samples of the classes desired, thus greatly simplifying and speeding the training of the classifier. The specific steps to be followed then are:

1. Decide on the list of classes and determine the general locality of examples of these classes, based on limited ground observation. This information may be from a low-altitude aircraft pass, information available from a perhaps out-of-date or inaccurate map, or a limited ground survey.
2. Designate these regions to the clustering algorithm and, after clustering, identify the specific clusters associated with the classes of interest.
3. From this point the statistics of each class can be computed from appropriate clusters and the classification can proceed.

In conclusion, it must be emphasized that the techniques are still evolving and are very experi-

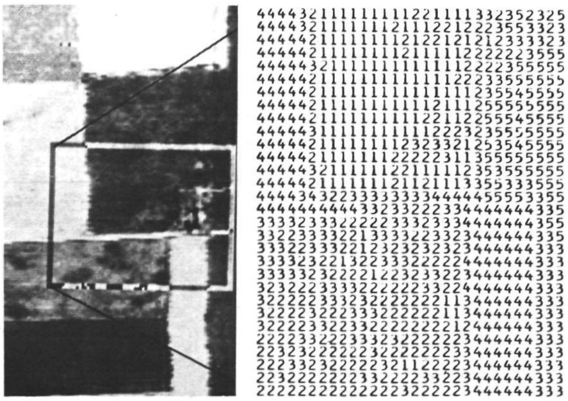

FIGURE 23. Clustered data using four spectral bands.

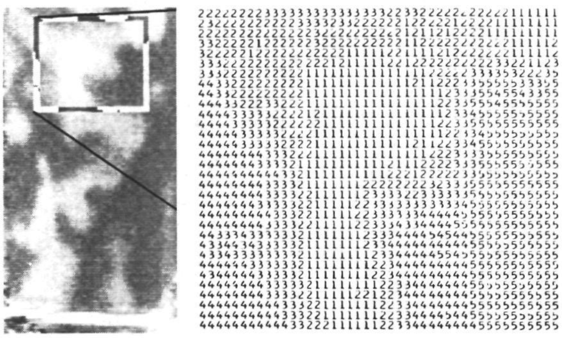

FIGURE 24. Clustered data from poorly defined classes.

mental in nature. Many questions about the utility of the extrapolation mode and machine-aided training procedures remain to be answered. Not the least

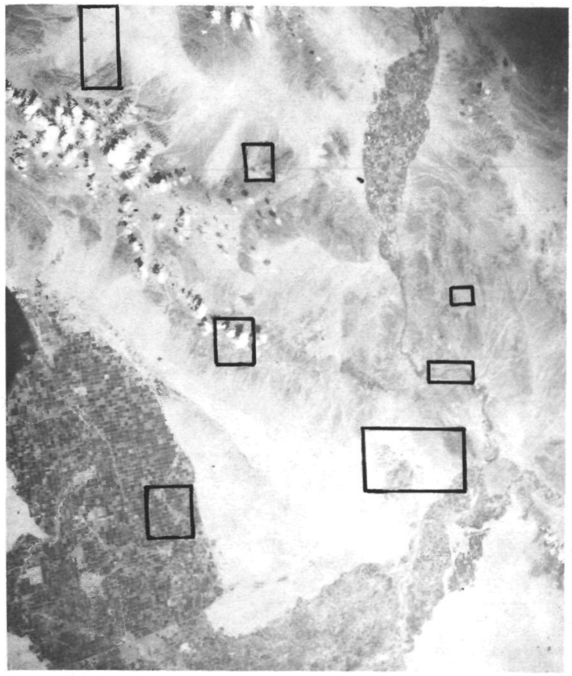

FIGURE 25. Cluster fields for machine-aided training.

of these are the extent over which a given classifier can generalize or extrapolate from its training areas and the extent to which machine-aided training procedures actually expedite the training of classifiers for practical situations. The Earth Resources Technology Satellite will, for the first time, provide a data base from which answers to these questions may be sought.

How Will the New Technology Enhance Capabilities to Collect and Analyze Earth Resource Data?

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Advances in sensor technology now allow us to sense radiation from the ultraviolet to the microwave regions of the spectrum. A number of consequences result from these expanded capabilities.

First, it is now possible to collect information under a variety of weather conditions; poor visibility is not necessarily a major barrier.

Second, the spatial recognition of objects, which depends on recognizing the object's shape and surrounding context, is now made easier because of the possibility of selecting bands in which the contrast is best represented.

Third, the availability of data in many spectral regions simultaneously permits the identification of objects by the spectral distribution of their reflected or emitted radiation. In addition, such spectral identification can be made automatically by the use of modern computing technology.

The result of these three considerations is that we are better able to obtain a maximum of information from the vast quantity of data our modern sensors are capable of collecting. The ERTS multispectral scanner and the Houston airborne multispectral scanner will be premium tools in this expanding technology.

Remote sensing has already come a long way in the United States. We have gone beyond the point of making simple surveys and have gone on to crop identification, yield prediction, and disease recognition as means of making more efficient use of our agricultural resources. However, remote sensing survey techniques may still have immense value in developing countries where sophisticated statistical services have not yet appeared. For example, the areas of cultivated lands are well known in the United States, but such information from aerial surveys may be of significant value to planners in developing countries. In these countries there may well be great value in modern sensor and recognition technology in areas no longer applicable in the U.S. It is therefore useful to go back and examine some of the past studies that have been made and consider their applicability elsewhere in the world. The data selected for this paper were collected in the period from 1960 to 1965. The system used for data collection was the Michigan DC–3 aircraft, camera systems (quite old), and the multispectral scanner.

SINGLE-BAND CONTRAST ENHANCEMENT

It is generally known that the contrast between the object that we seek to find and its background can be enhanced by appropriate selection of the spectral band using laboratory measurements of reflectivity and emissivity for both target objects and background objects. In the examples that follow, I present only a few of these cases. Others have been produced by simple filtering of photography or by the multispectral scanner that we use at the University of Michigan. More advanced infrared scanners and various radars will be covered briefly later in this paper.

In the first example (figure 1) we see a picture of a rural area. The scene contains roads, some fields, and a few buildings. We note that in the 0.32-to-0.38-μm band most of the contrast in the scene

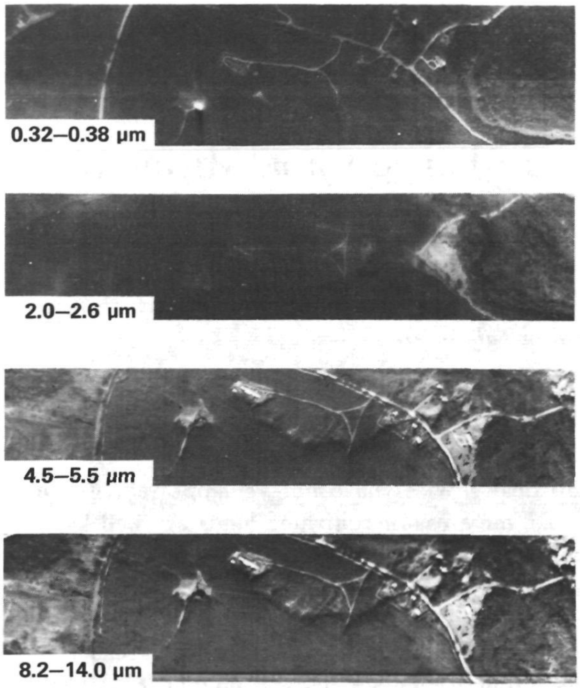

FIGURE 1. Effects of multispectral imagery on contrast.

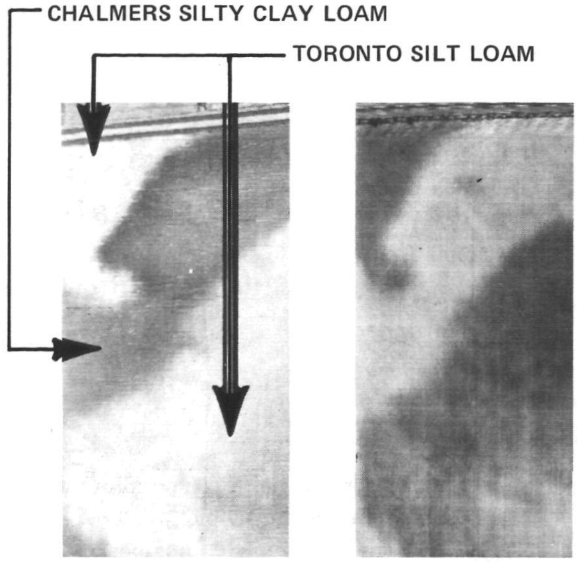

FIGURE 2. Comparative contrast of soil types in different spectral bands.

has been eliminated except for the roads and the one fairly bright tin-roofed building in the scene. As we look at the other bands in the imagery, we see much more general contrast, highlighting various terrain areas, but the building no longer stands out quite as clearly as it does in the top photograph. Figure 1 illustrates two points: (1) that some objects appear in one spectral band but not in others and (2) that appropriate selection of spectral bands eliminates unwanted contrast. The illustration used here demonstrates a possible application for census of housing in developing countries, where tin roofs are sometimes used. In figure 2 we see a second distinction between the 0.32-to-0.38- and 4.5-to-5.5-μm bands. In this case we are seeking contrasts between two different soil types. We see in the two images that both spectral bands show a contrast between the clay loam and the silt loam. While we might at first select the 0.32-to-0.38-μm band, it is fairly evident from the image that a considerably more regular contrast can be obtained in the 4.5-to-5.5-μm band, with the added advantage that the contrast is available in the nighttime hours.

Figure 3 shows images of a potato field, collected in two wavelength bands. The bright area in the lower image is a pigweed infestation in a potato field. The differences in reflectivity between the pigweed and potato illustrate the different percentages of ground cover occupied by weeds and potatoes in the two crop areas. The contrast in the 2.0-to-2.6-μm band therefore emphasizes such conditions as weed infestation in fields.

Because no single band is useful for all identification purposes, the ability to select one band for a particular identification and another band for others provides the power to solve several problems simultaneously. The selection of spectral bands depends on the object we seek to distinguish from the backgrounds. Collecting data in more than one band is important if we would have optimal contrast for all types of problems. Let us turn our attention to yet a different problem.

A major resource of any country, developed or developing, is water. One type of water resource is the ground moisture. Figure 4 shows a moist area. The lower portion of the figure is an infrared image taken from an altitude of 900 m. The upper image is a panchromatic photograph, taken at ground level, of the same area, with the wet spot fairly well delineated. The very clear contrast in the 0.85-to-0.89-μm band is to be expected because the reflectivity of moist soils is in general much less than that of dry soil, regardless of the type of soil.

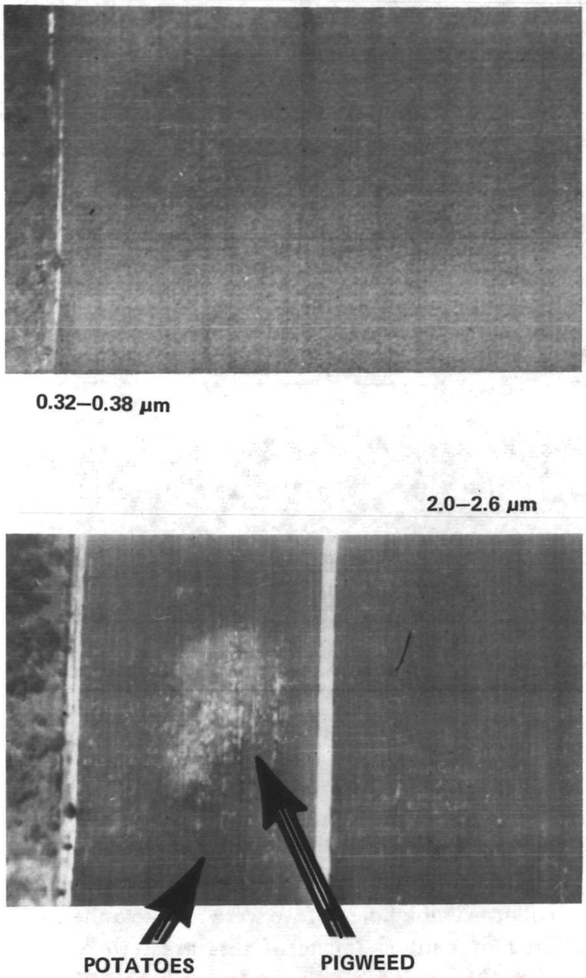

FIGURE 3. Comparative contrast of vegetation types in different spectral bands.

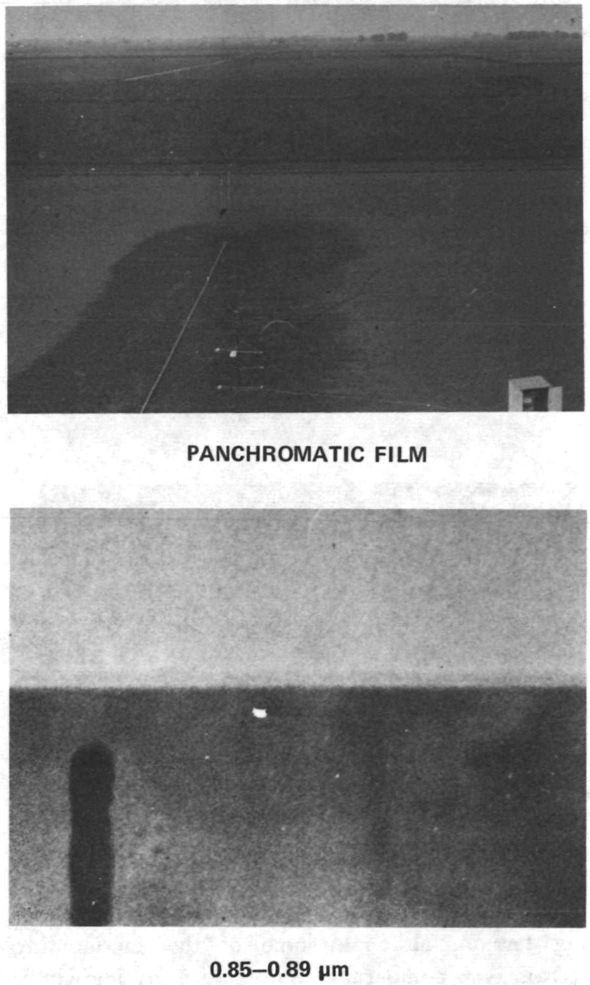

FIGURE 4. Contrast of soil moisture differences in aerial IR photo compared to ground panchromatic photo.

Thus, in looking at an infrared aerial photograph collected in the 0.85-to-0.89-μm band, we expect to find moist areas which are darker than those that are drier. Therefore, if we are looking for water or moist soil photographically, we should consider the 0.7-to-1.0-μm band as being most appropriate. If we use not only photographic equipment but also IR scanner equipment, we find even more appropriate bands for detection of water.

Figure 5 shows a time sequence of three images of a bog area collected in the 4.5-to-5.5-μm region. In this imagery we are looking at emitted radiation from the terrain, rather than reflected energy. All reflected radiation has been filtered out to insure that we see only the emitted signal. The bright area in the predawn image is the water; the surrounding terrain cools considerably more during the nighttime than does the water, since the thermal capacity of the water is greater than that of the terrain. After dawn the contrast begins to fade, until by midmorning the water appears cooler than the surrounding terrain. Thus, although contrast varies at different times of day, water is clearly detectable both day and night, provided the atmosphere allows us to see through it.

We should note that atmospheric transmission is considerably superior in the longer wavelength band, and in general we can see through more haze in the infrared region than we can in the visible.

Because emitted radiation is closely connected to the temperature of the terrain, we may also expect to see a seasonal variation in the contrast. Figure 6

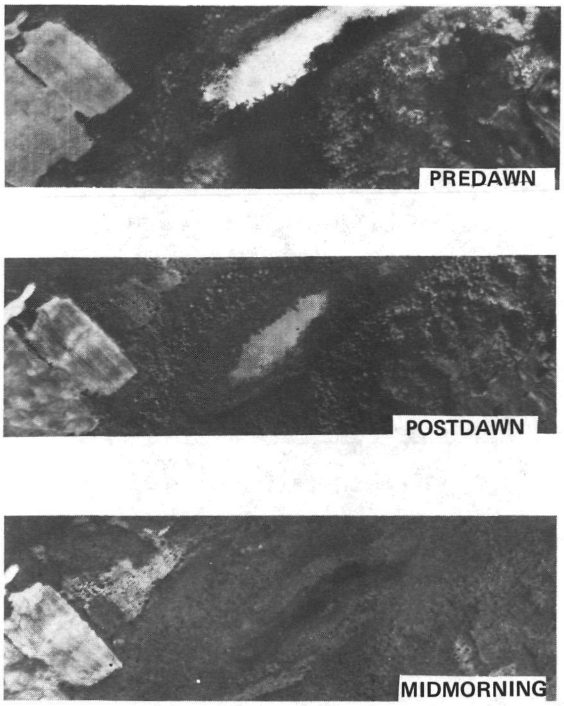

FIGURE 5. Night-to-day transition in contrast of bog area recorded in 4.5-to-5.5-μm band.

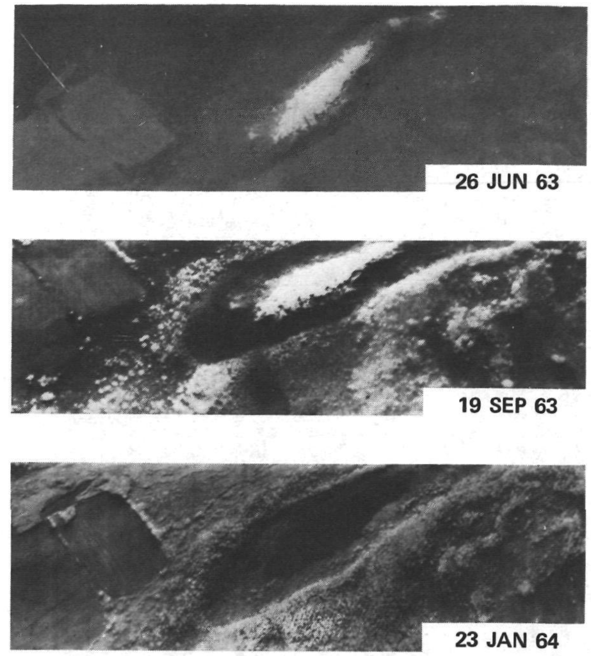

FIGURE 6. Seasonal variation in contrast (bog area photographed in 4.5-to-5.5-μm band between midnight and dawn on dates shown).

shows a seasonal comparison of the same bog area (in Michigan). In June the water after midnight is warmer than the land, as would be expected. In September the water is still warmer than the surrounding terrain, although some of the surrounding terrain is of comparable temperature. By midwinter the water has of course frozen and is considerably colder than the surrounding terrain. The interpretation of infrared emission imagery must therefore take into account the season as well as the time of day. This imagery shows clearly that the detection of both standing water and surface soil moisture is greatly facilitated by use of the infrared bands.

Remote detection of reflected electromagnetic radiation is useful not only in determining the surface condition of the terrain, but can also be used to infer conditions below the surface, such as subsurface water. Figure 7 shows an area of sink holes in Florida. The sink holes are produced when limestone substrata are dissolved by water, forming a cavern which eventually erodes to the point where the surface collapses. When the surface collapses, the sink hole is easily detectable, but by then it is too late to do anything about it. The detection job, in general, is to determine potential sink hole areas prior to collapse. The sink hole area of concern is in the dotted outline in figure 7. Notice also the area at the left center of the image where the roads intersect. The circular areas inside the dotted patch are collapsed sink holes. If we were to take a thermal infrared or emitted image of this area, we would see that the eroded cavern underneath the surface exhibits a thermal capacity greatly differing from that of the surrounding solid terrain.

Figure 8 shows the thermal contrast in the area of sink holes surrounded by the dotted line in figure 7. Note the cold region (figure 8) where the sink hole appears in the infrared photography (figure 7). Note also the additional dark areas at the left-hand side of the image. These areas do not show collapsed sink holes, but sink holes where no surface manifestation has yet occurred. The presence of sink holes was verified by ground observation after this imagery had been collected.

Figure 9 shows multispectral imagery of sea ice in the Smith Bay area. The visible and reflected IR regions show considerable contrast, cracks in glare ice, and other phenomena. The reflective bright patches in the upper two reflected images, corresponding to dark areas in the emission imagery, are solid ice packs which are considerably colder than the surrounding area and more re-

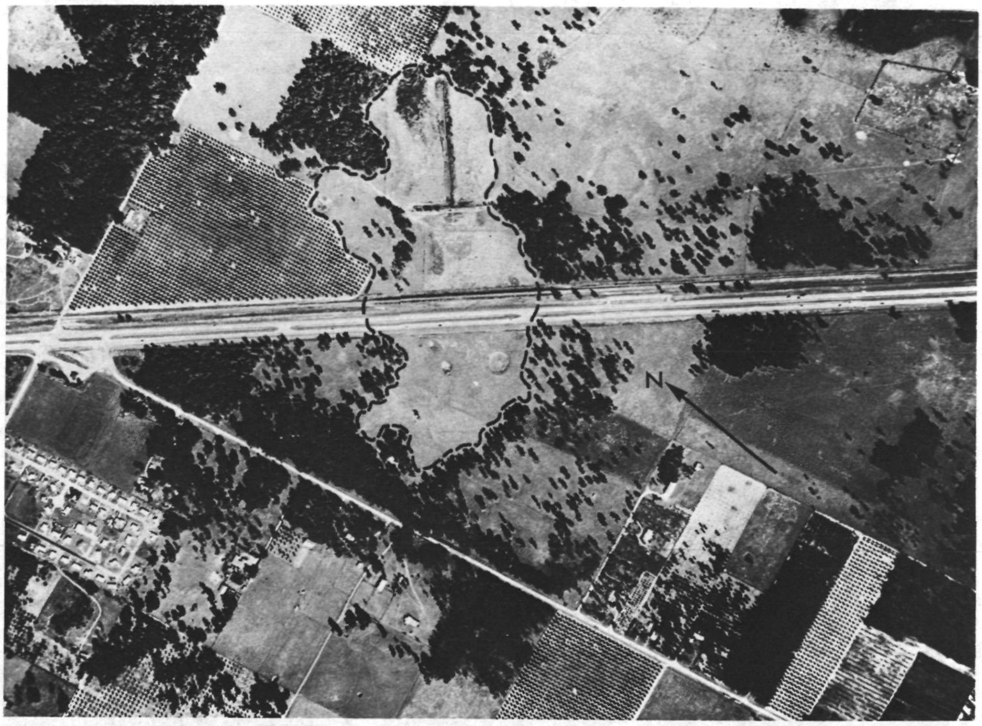

FIGURE 7. IR color photo of sink hole area.

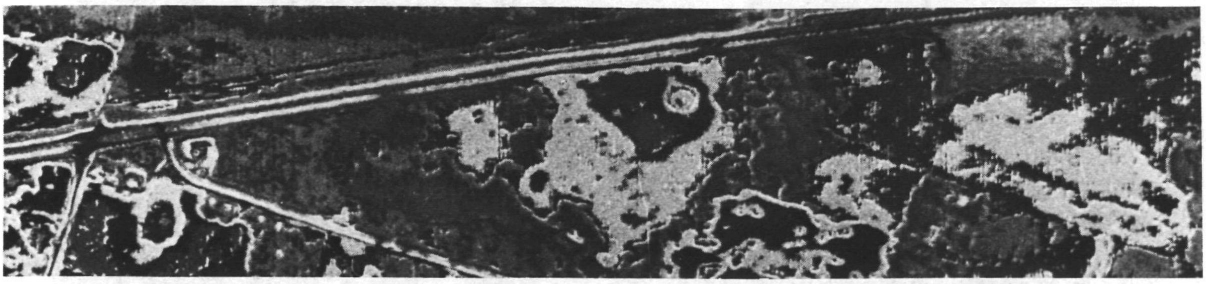

FIGURE 8. Color-coded thermal contour map of sink area. Black=27.8 °C; yellow=28.7 °C; red=29.4 °C; blue=30.3 °C.

flective. The use of two or more images to determine the content of the scene is, of course, the beginning of a multispectral analysis.

We now move from passive detection systems to an active system using radar. Figure 10 shows two radar images of an agricultural area around Garden City, Kansas. The upper image is polarized horizontal-horizontal, and the lower image horizontal-vertical. The wavelength is K band. The area marked A, a small circular light outline, is a swamp area. Its counterpart in terms of water content is the area marked B, an irrigated area with an overhead spray. The area marked C in the upper image contains sugar beets, whose rather broad leaves are efficient reflectors because of differences in orientation. Today we have very little information about the interpretation of radar imagery because of problems in separation of geometrical from optical properties. As work progresses, however, we certainly may expect increased sophistication in the interpretation of radar imagery.

So far we have covered fairly simple systems for collecting imagery in single spectral bands. From them we may draw some fairly elementary con-

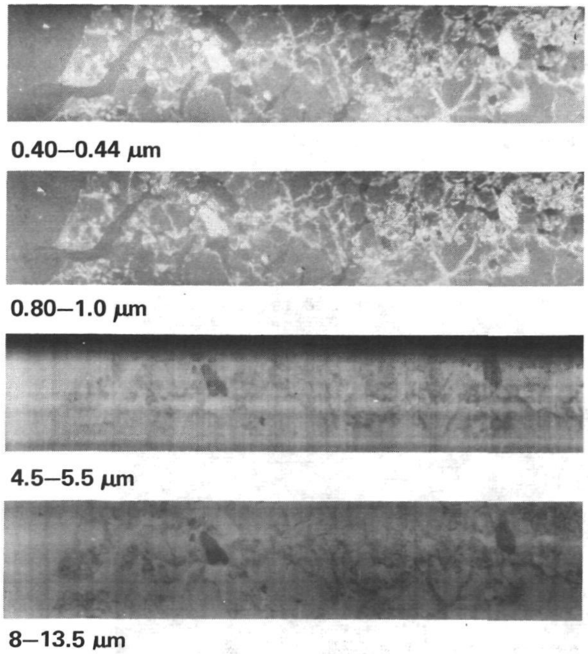

FIGURE 9. Images of sea ice in Smith Bay taken in four spectral bands from 600-m altitude.

clusions. First, there are good reasons to carry a multiplicity of sensors aboard any platform. We see that, for various applications, different spectral bands give us optimal contrasts, and so we should consider not only photographic instrumentation but infrared and radar as well. These may be separate instruments in different wells in the aircraft. In fact, we at Michigan have for many years carried separate instruments operating in a multiplicity of bands.

MULTISPECTRAL PROCESSING

The basis for multispectral processing is the distribution of the received radiance from terrain objects. Recognition is based upon this spectral distribution of radiance for each resolution element of the scene. As a consequence, we must have a single-aperture instrument so that for every resolution element on the ground we are able to measure this spectral distribution of radiance. A number of such instruments are available today.

The basic instrument is an electrooptical scanner that is commonly used for infrared imagery. In place of a single detector, it has an entrance slit for a spectrometer whose dispersing element is either a prism or a grating. The dispersed spectrum is detected by a number of individual point detectors placed in the dispersed spectrum. The detector outputs are recorded in either analog or digital form on magnetic tape.

The first of these instruments was built at the University of Michigan and operates in the 04.-to-1-μm band. Subsequently, NASA has sponsored the development of a 24-band instrument operating in the 0.4-to-14-μm region. The ERTS-A instrument is the first of the spaceborne multispectral instruments, with four bands in the 0.4-to-1-μm region. The EREP package of the Apollo Skylab project is a 10-band instrument operating in the 0.4-to-14-μm region. While these instruments sound fairly complex, they are in fact fairly simple. Although the main intent is to produce data for multispectral processing, the imagery can be used as if it were produced by single-band instruments, and the interpretation would proceed as discussed above.

Before we begin a general description of multispectral processing, let us consider a few fairly simple examples. It is well known that the penetration of water by light depends on the wavelength of the light. Figure 11 shows images selected from various spectral bands of some water scenes from the Caeser Creek area off the coast of Florida. Note that the peak penetration is in the green portion of the spectrum. In the 0.8-to-1-μm band, only the land outlines are visible. The differential penetration of light in the various spectral bands can be used to estimate the water depth. It turns out that the formula for estimating this depth depends upon the ratios of the scattering coefficients of the water and the bottom reflectance in two bands. These ratios are fairly constant for most bottom types and most water types. With *a priori* estimates of the ratio of scattering coefficients and the ratio of bottom reflectances in the two bands, we may then estimate the water depth.

A computer map of the calculated water depth for the Caeser Creek area is shown in figure 12. It shows good comparison with the actual chart recordings shown in figure 11, except in the channel area. Here, the water depths are underestimated because of heavy silt concentrations. The depths estimated are really effective depths, including the amount of silt suspended in the water. This use of multi-

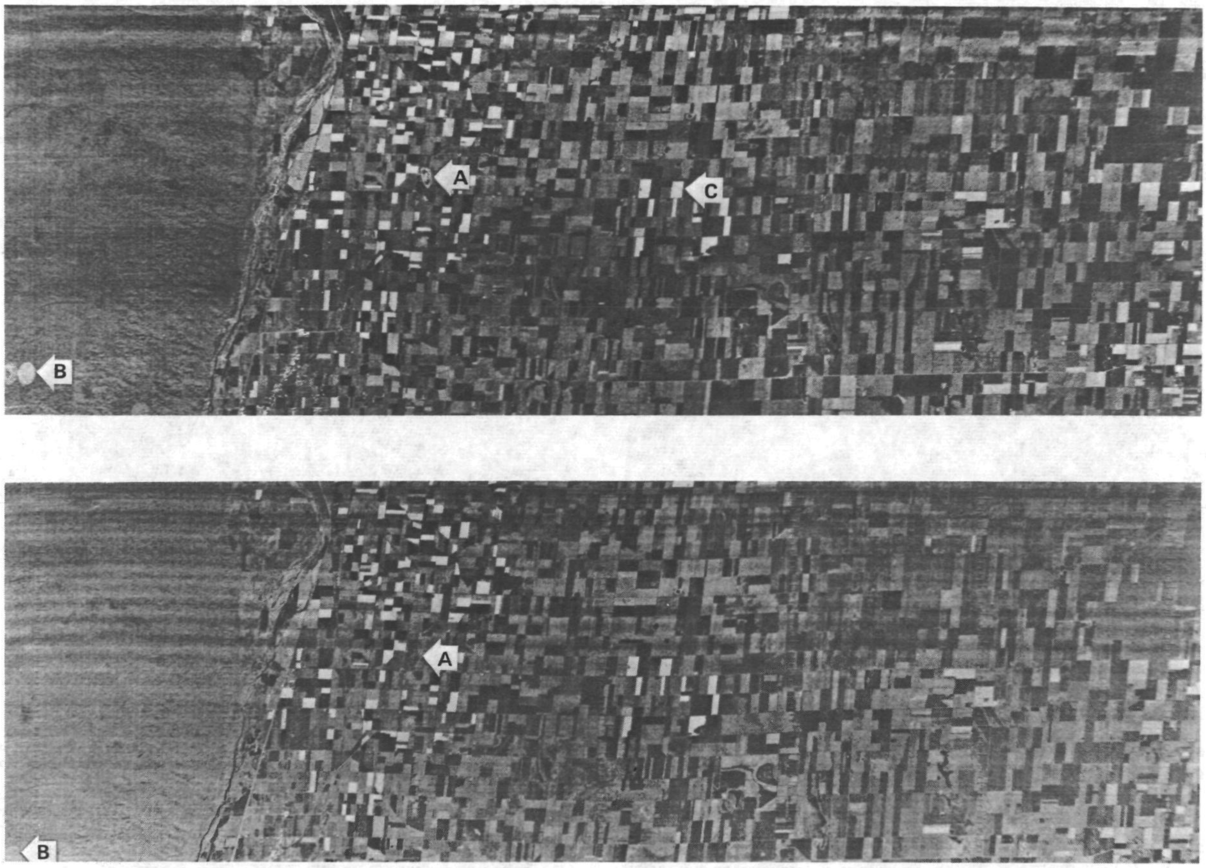

FIGURE 10. K-band radar images of farmland near Garden City, Kansas. Upper image is polarized horizontal-horizontal; lower image, horizontal-vertical. A, swamp; B, area irrigated by sprinklers; C, sugar beets.

spectral data involves specialized calculations to provide the depth.

Another example is indicated by figure 13. Silicate rocks are classified acidic or basic, roughly on the basis of their silicon dioxide content. The silicates exhibit reststrahlen absorption bands in the 8-to-14-μm region. The position of the minimum of this reststrahlen emissivity depends upon the acidity or the percentage of silicon dioxide in the rock, as shown in figure 13. Generally speaking, rocks with less silicon dioxide content have reststrahlen minima at longer wavelengths. In figure 14, imagery from fairly simple laminar detectors in the 8.2-to-10.9- and 9.4-to-12.1-μm bands shows how this effect is exploited. The three images shown are of a sand quarry near Mill Creek, Oklahoma. The laminar detectors are in fact two detectors, one placed on top of the other so as to measure two bands simultaneously. By taking the ratio of the two bands, we are able to identify the quarry area shown in the right-hand image of figure 14. Note also the outline of the body of water, which is rimmed by quartz sandstone outcroppings.

These examples are fairly special cases of multispectral processing. Let us turn our attention now to some more general instrumentation and some more general examples, keeping in mind that this general instrumentation is capable of doing the tasks that we have already described.

Figure 15 shows a panchromatic mosaic of a California farming area including fields of rice and safflower and some bare fields and roads. Figure 16 shows images of the same area collected in separate spectral bands with a multispectral scanner whose dispersion is achieved by a prism, with a common spatial aperture for all spectral bands. The

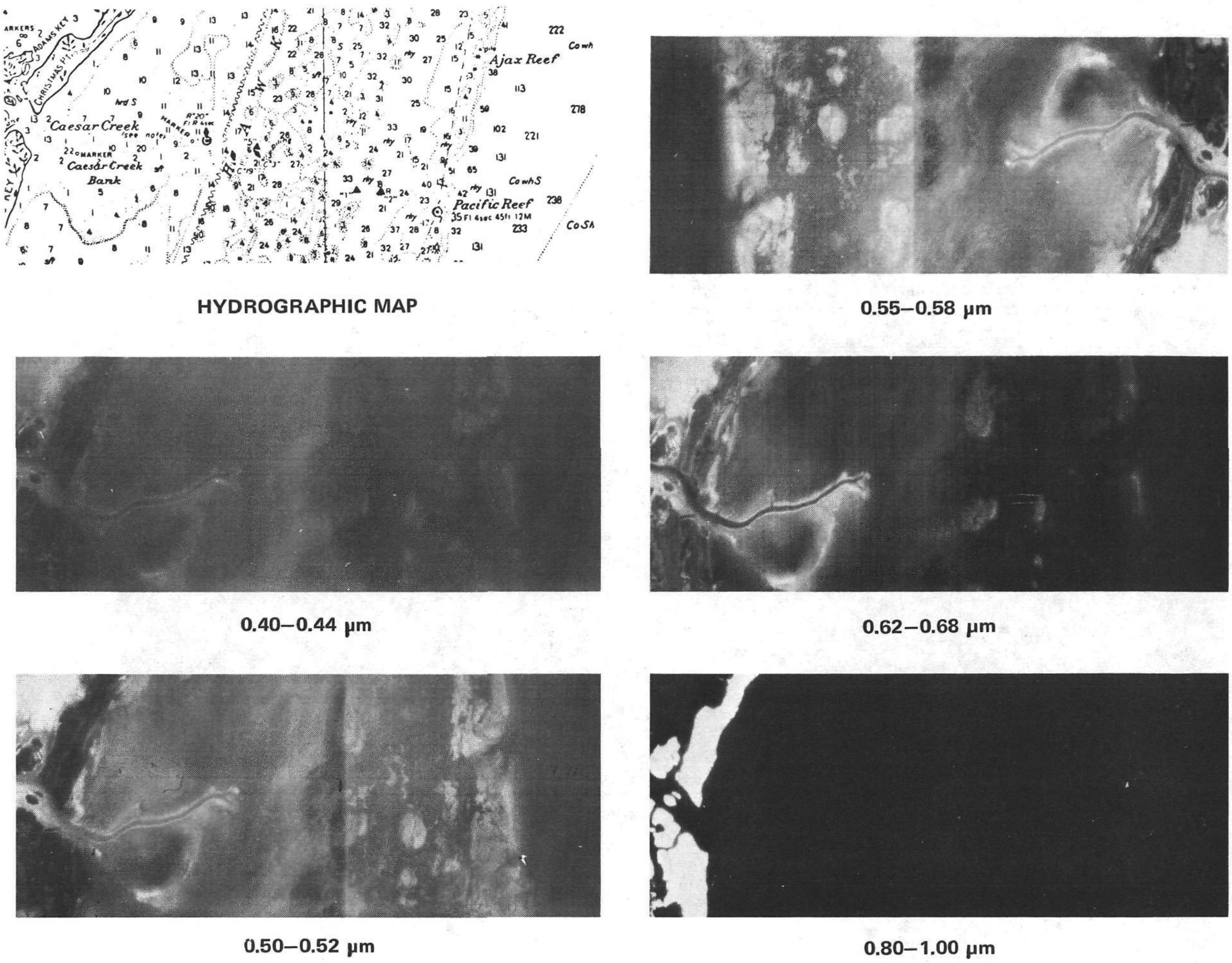

FIGURE 11. Multispectral mapping of Caesar Creek and Pacific reef.

signals from the 18 channels are then analyzed using standard statistical discrimination techniques to identify the objects in the scene, in this case the various fields. The parameters of statistical procedures are obtained by taking training samples of the various object types, such as immature rice, mature green rice, bare earth, roads, and safflower.

In figure 17, important areas of crop have been appropriately identified in a digital recognition map. The importance of the multispectral scanner lies in the fact that it can be used for automatic discrimination, as in this example.

Modern sensor instruments are capable of producing information much faster than a human interpreter or group of human interpreters can handle it. Multispectral methods provide a fairly simple and straightforward way to aid the interpreter in obtaining from data collected by sensors the information he seeks.

The human interpreter still must specify the training sets for our statistical procedure. But the automatic interpretation device extends possible identification into areas beyond those which the interpreter can identify. It is also able to perform a number of other routine tasks for the interpreter, such as the measurement of area, the measurement of perimeters of areas, and other numerical operations.

In the previous discussions we have shown how simple it is to identify the presence of water. In this next example, we are concerned with finding ponds of water for the purpose of estimating duck popula-

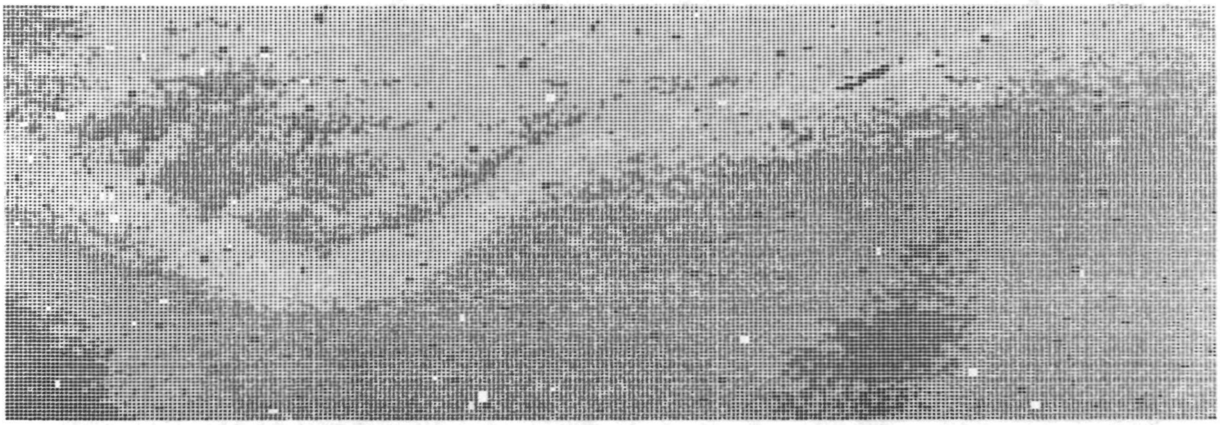

FIGURE 12. Computer map of calculated water depth for Caesar Creek.

tion. Estimates of duck population depend not only on the water area, but also on the shape of the pond. An irregularly shaped pond is capable of supporting a larger duck population than a more nearly circular pond of the same area. The water is identified automatically and recorded on digital maps such as that shown in figure 18. The computer is programed to calculate the area and perimeter of each pond, as well as a shape factor which is related to the estimate of duck population.

We saw before that one of the purposes of multispectral processing is to extend the ability of the interpreter to identify certain areas both spatially and temporally. There are a number of atmospheric effects which interfere with this extension of the learning set. Objects in the scene have different optical characteristics depending upon the illumination and viewing angles used. Certainly shadowed and sunlit areas look considerably different. As a consequence, we find variations in the spectral signatures of objects that are not related to the terrain itself but rather to variations in the atmosphere, transmission, illumination, and backscatter. These atmospheric variations are, of course, noise to the system. There are, in fact, three rather general methods used to eliminate these variations. The first is to pick some transformations on the data, the result of which is to leave the multispectral data relatively invariant under variations in the atmosphere. The second is to use ancillary instrumentation to measure the atmosphere in terms of such quantities as illumination at the sensor platform. Laser probes can be used to measure backscatter. The third method is to select references against which to measure atmospheric effects.

Figure 19 illustrates these effects. The two axes represented are signals from spectral channels i and j. Variations in angular effects have been shown to be approximately linear, as are those for illumination effects. As a consequence, we might expect that the ratio of adjacent spectral channels (S_i/S_{i+1}) will be invariant with respect to variations of the atmosphere.

Figure 20 shows recognition maps for soybeans in an area containing both corn and soybeans when there are cloud shadows over the area. In the upper map a considerable portion of the field has been missed. The ratio preprocessing technique of S_i/S_{i+1} used for the lower map shows recognition of the entire field area.

These preprocessing techniques are in very early stages of development. So far they have enabled us

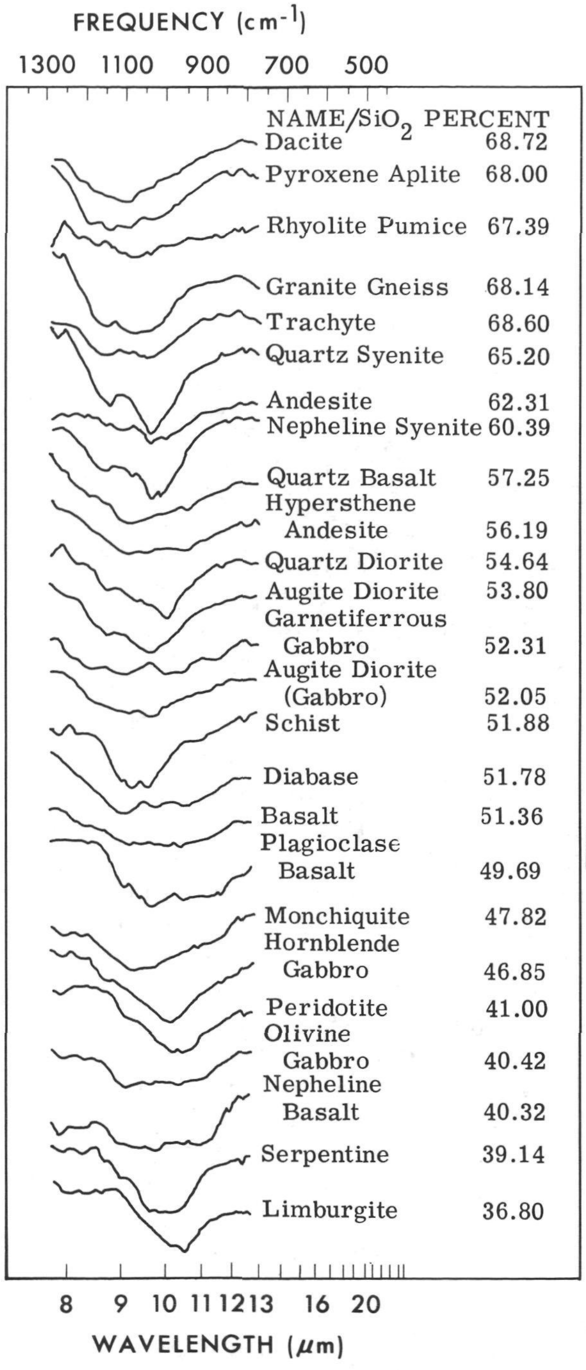

FIGURE 13. Emissivity spectra of silicate rocks.

to extend signatures in some cases for as much as a year in time and over 160 kilometers. But there are still many cases where such extension is not possible. It is not possible to say at this time how far we will be able to extend signatures, but it is our expectation that they will be extendable over long periods of time, certainly over many seasons or years and over many thousands of kilometers.

The implementation of these automatic recognition techniques is, of course, somewhat more sophisticated than the human interpretation that we discussed in the previous section. It requires fairly standard general-purpose digital computing equipment that is easily implemented. That such recognition techniques are worthwhile seems obvious. Whether or not they are practical for developing countries, in terms of scale of operation, we are not in a position to say, although it appears very much as if they would be.

INSTRUMENTATION

The foregoing examples have indicated the wide scope and numerous applications of narrow-band and multispectral remote sensing. As the science has developed and the applications expanded, so too has the instrumentation advanced to surprising degrees of sophistication. It runs the gamut from satelliteborne multispectral scanners to automatic-discrimination computers. Currently, much of the elementary remote sensing equipment is becoming available at reasonable cost to new entries in the field. The basic requirements for a remote sensing system are described briefly below.

Certainly the basic necessity for any remote sensing program is the airplane—the airborne platform for the sensors. The type of airplane used is highly dependent on what is available to the experimenter, with certain minimum requirements. As a beginning, much can be done with a single-engine propeller aircraft. Desirable features are: reasonable maintenance costs, nominal four-place capacity to provide adequate space for instruments and crew; high-wing construction to enhance visibility and facilitate instrument installation; low speed and high stability; and range compatible with the type of mission and the airport facilities available in a rural area.

In the early days of remote sensing at the University of Michigan, the DeHavilland Beaver (L–20) shown in figure 21 served this purpose well. Two of these reconnaissance-type aircraft were obtained

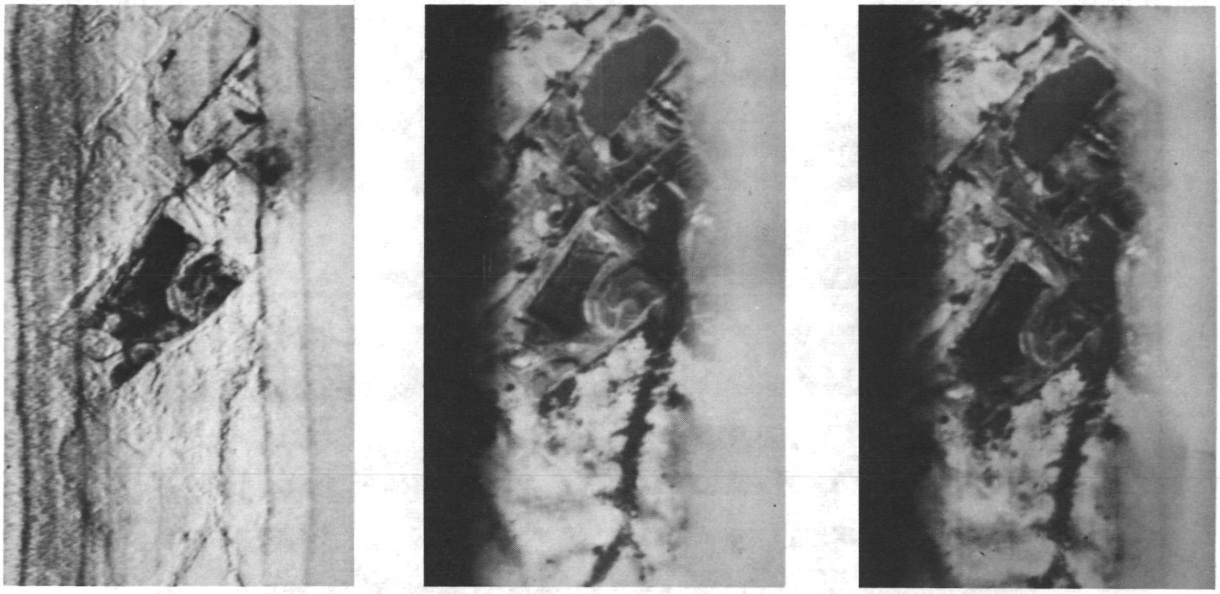

FIGURE 14. Discrimination of acidic silicates near Mill Creek, Oklahoma.

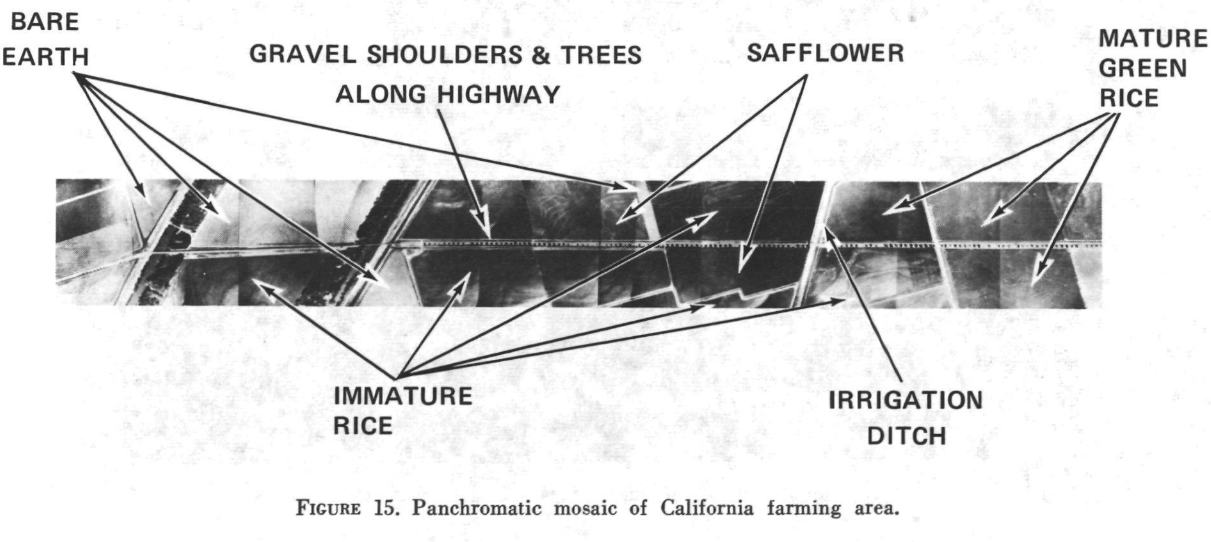

FIGURE 15. Panchromatic mosaic of California farming area.

on loan from the United States Army. When a mission required more equipment than could be carried by one airplane, two were used as illustrated in figure 22. Of course the registration of the data obtained is something less than perfect, but the basic data needed for exploratory studies has been obtained in this way.

As indicated in figure 22, each airplane carried a K–17 and a P–2 camera and an S–5 infrared scanner and film printer. Figure 23 shows the scanner installation and the operator's position inside the aircraft, while figure 24 shows the mounting of one of the cameras (K–17) outside the aircraft. A somewhat more sophisticated aircraft (Fairchild

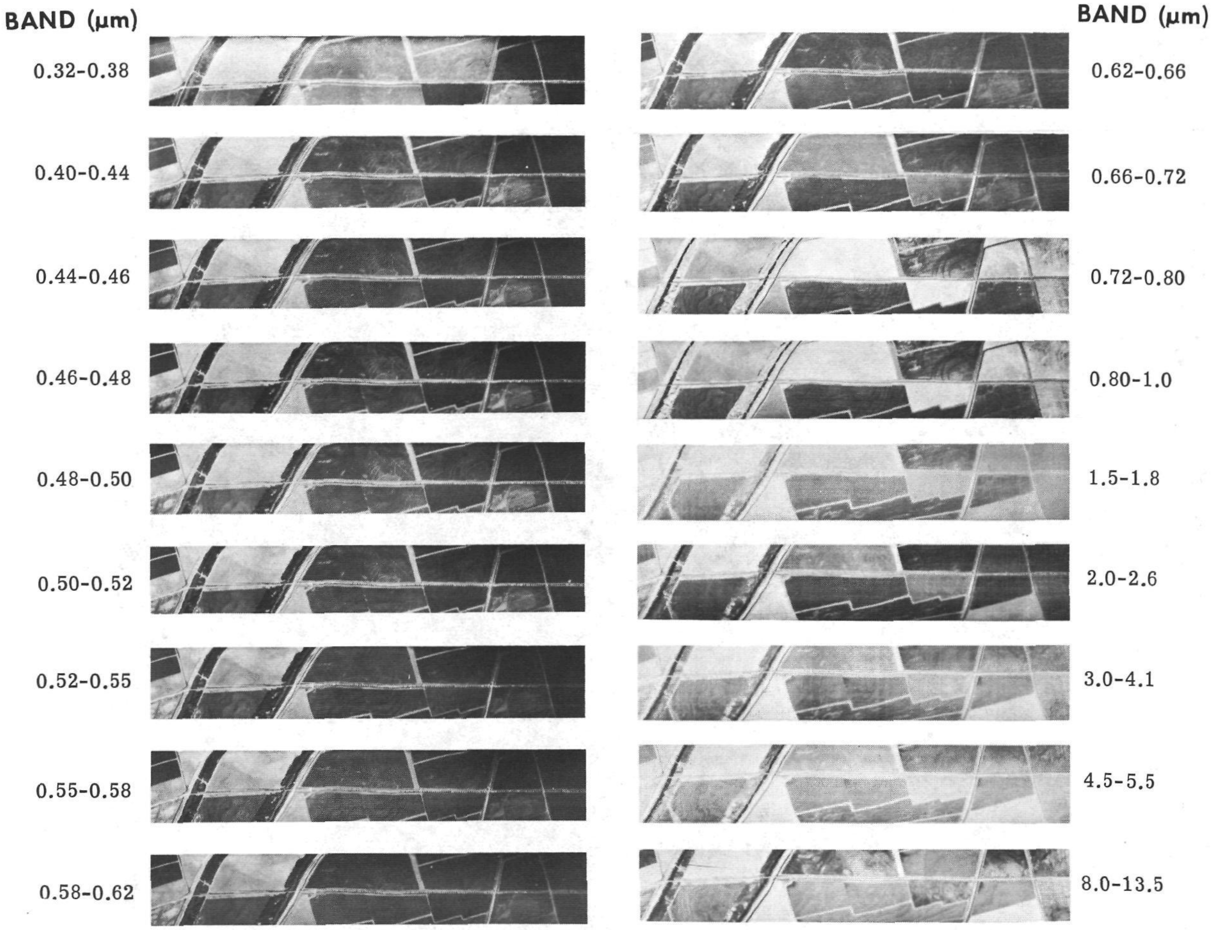

FIGURE 16. Multispectral imagery of area shown in figure 15 (Davis, California) taken at the same time from the same altitude (600 m).

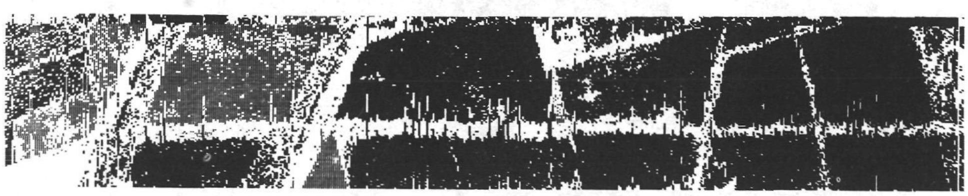

FIGURE 17. Digital recognition map of area shown in figures 15 and 16.

Hiller Heli-Porter turboprop), with the sensor installation currently used by a commercial remote sensing agency, is illustrated in figure 25.

The camera it still a basic tool in airborne remote sensing. A wide variety of film and filter combinations (both black-and-white and color) are available in the visible and near IR regions (0.5 to 0.88 μm) which lend themselves to multispectral studies.

Many fine aerial cameras in a variety of formats ranging from 70 mm to 23 cm are available from companies in the United States dealing in government surplus equipment. Typical unit costs range from \$100 to \$300, depending on the lenses and condition. Intervalometers, gimbaled mounts, remote controls, filters, and a wide range of film types all are available at reasonable cost to increase

FIGURE 18. Digital computer gray map of ponds in Woodworth study area, North Dakota, from imagery taken in 1.5-to-1.8-μm band at 600 m.

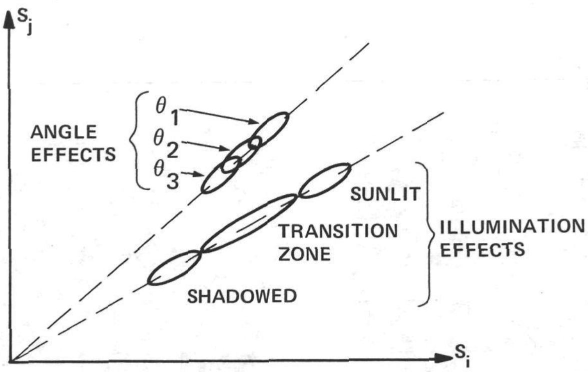

FIGURE 19. Effects of multiplicative factors on signal scatter diagram.

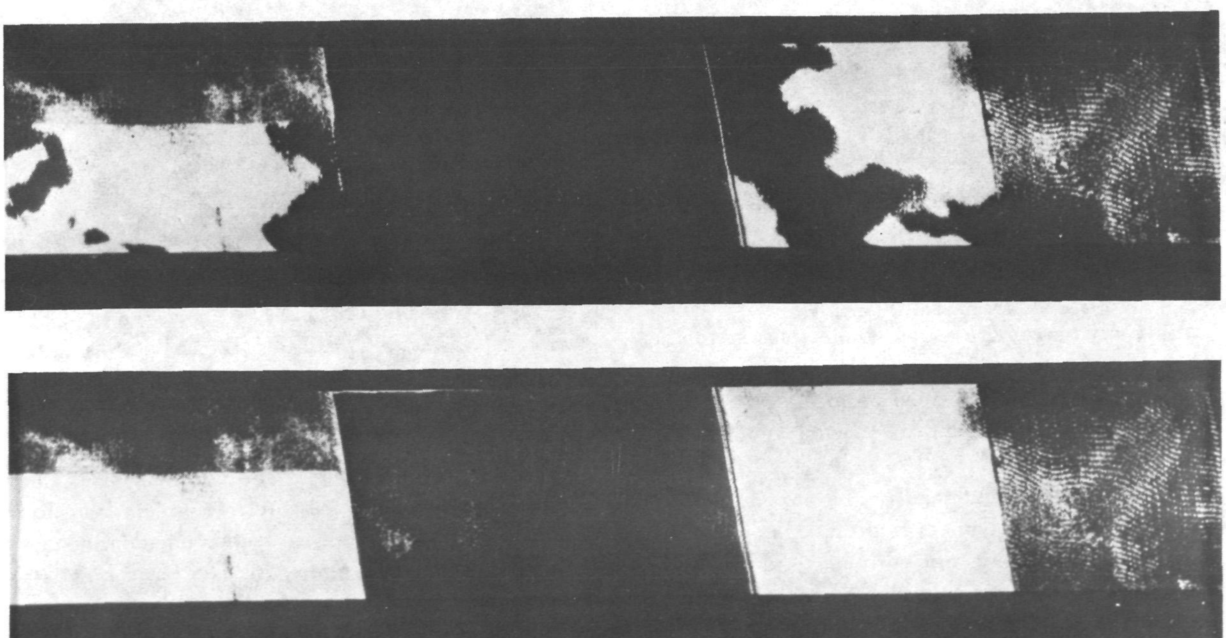

FIGURE 20. Soybean recognition maps using (top) a target signature derived from a shadowed area and (bottom) a bimodal target signature map.

FIGURE 21. DeHavilland Beaver (L–20) aircraft used for remote sensing at the University of Michigan.

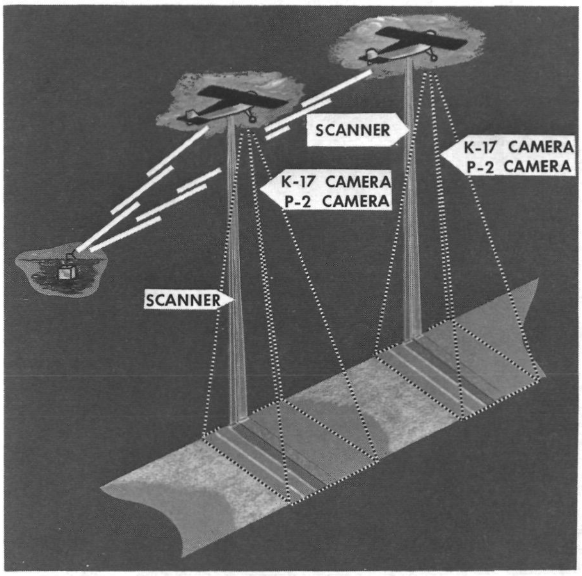

FIGURE 22. Schematic of airborne operations.

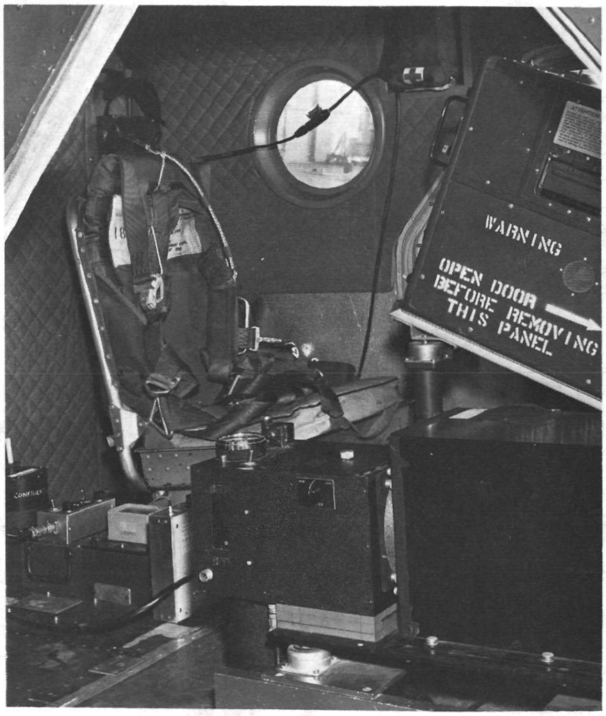

FIGURE 23. Scanner installation in L–20 aircraft.

the utility of the camera as a remote sensing tool. Sources of surplus (new and used) aerial camera equipment are readily obtained from the advertisements in the numerous optical journals published in the U.S.

Similarly, anyone financially able to take advantage of the latest advances in aerial camera technology will find many fine products advertised. Initial costs might be roughly triple those of similar used (surplus) equipment.

Very often, original effort can produce results not otherwise obtainable. For example, one of the original multispectral research tools used at the University of Michigan was the homemade nine-lens camera illustrated in figure 26. The basic unit is a K–17 case with a 23-cm format. The filter plate assembly, also shown in figure 26, permits taking nine simultaneous pictures in different spectral

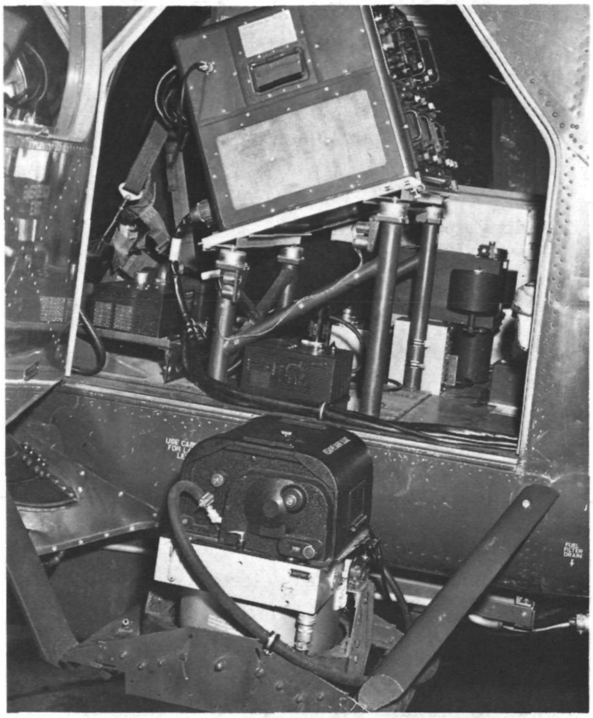

FIGURE 24. Aerial camera mounted outside L–20 aircraft.

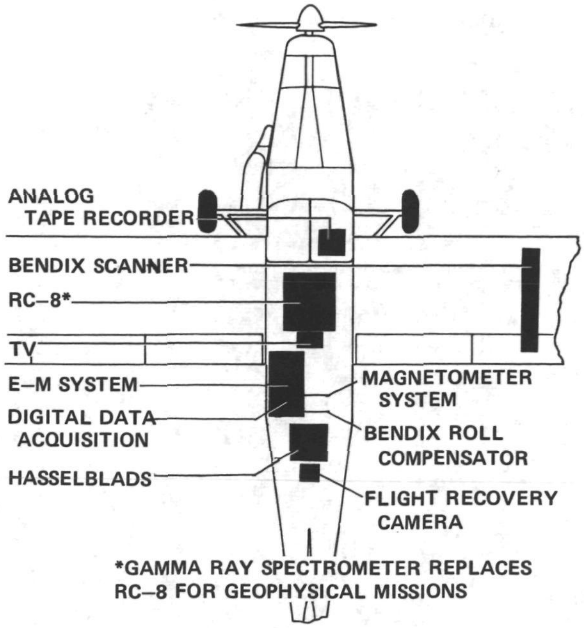

FIGURE 25. Instrumented Heli-Porter aircraft for remote sensing.

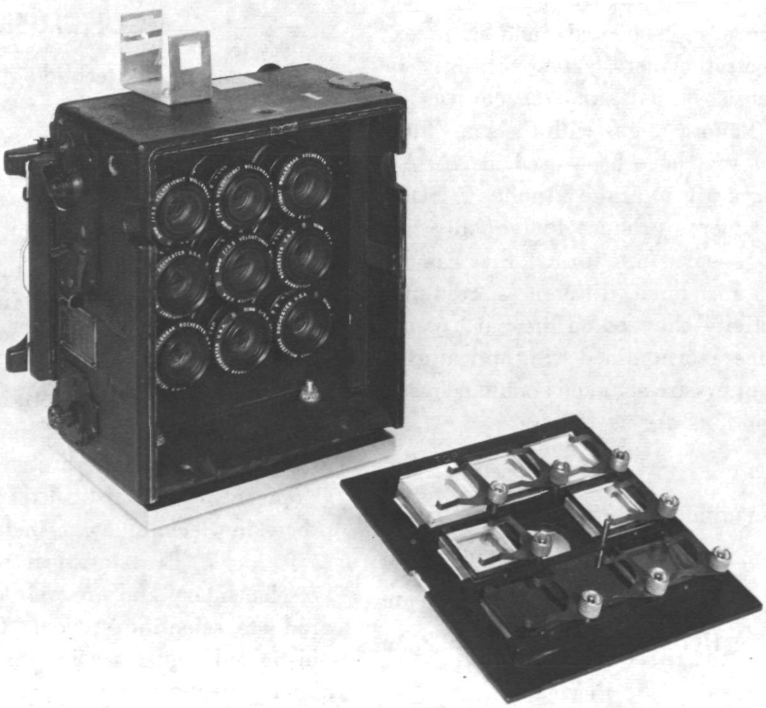

FIGURE 26. Nine-lens camera and filter plate devised at the University of Michigan.

bands, all in satisfactory registration. An example of the output is shown in figure 27.

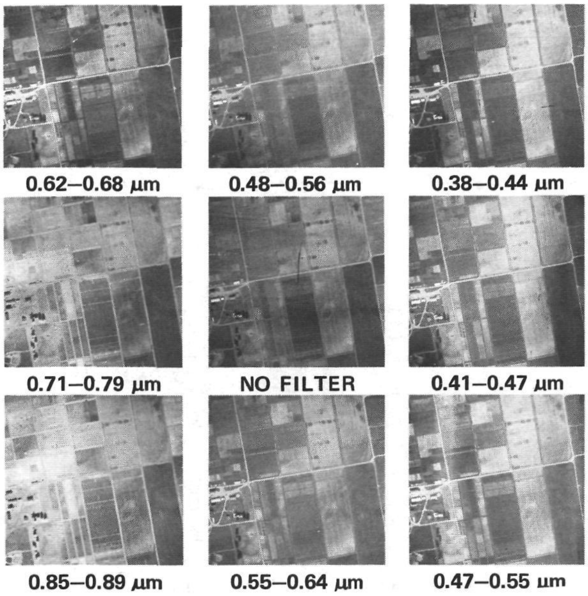

FIGURE 27. Image format of nine-lens camera, showing typical multispectral imagery.

A somewhat more sophisticated (and more expensive) multispectral camera array currently in use by a commercial aerial surveyer consists of four Hasselblad 70-mm cameras with the same film-filter combinations that have been used in NASA's remote sensing aircraft and the Apollo 9 SO65 experiment. The cameras produce high-quality images on a 70-mm square film format that can be readily examined for tonal differences resulting from subtle reflectivity changes on the Earth's surface. The four cameras are alined with optical axes parallel, and all shutters are actuated simultaneously. Film-filter combinations are as follows:

Camera	*Film*	*Filter*	*Spectral band*
1	3400 (Panatomic-X)	25A	0.60 to 0.70 μm
2	3400 (Panatomic-X)	58	0.50 to 0.58 μm
3	5424 (B&W IR)	89B	0.49 to 0.88 μm
4	8443 (Color IR)	15	0.52 to 0.88 μm

To perform studies in the thermal infrared regions an optical scanner is an absolute necessity, since photographic films do not extend beyond 1 μm. But here modern technology has done even more to help the beginner get started at a reasonable cost. Relatively inexpensive infrared scanners are now available commercially in the United States. Notable examples include the following:

Manufacturer	*Model*
Bendix Corporation Aerospace Division Ann Arbor, Michigan 48107	TM/LN–3 Thermal Mapper
Daedalus Enterprises, Inc. Ann Arbor, Michigan 48106	Airborne Line Scanner
H.R.B. Singer, Inc. State College, Pa. 16801	Reconofax IV and VI
Texas Instruments, Inc. Equipment Group Dallas, Texas 75222	RS–130 Infrared Line Scanner

In each case the scanner is a somewhat modular device, in that various detectors and auxiliary equipments can be incorporated to fit the needs and budget of the user. The prices of the equipment listed above range from roughly $25 000 for a bare scanner to perhaps $75 000 for a complete airborne set of instrumentation. Figures 28 through 31 illustrate additional details of this equipment.

CONCLUSIONS

Modern sensor technology has developed the capability to construct images in almost all portions of the electromagnetic spectrum. The necessity for such multispectral imagery seems evident if we consider the problem of contrast alone, which in some cases involves simply making the target visible against the background. Furthermore, the capability to produce multispectral imagery provides for automatic processing. If we consider the large areas surveyed in many of the developing countries, this automatic processing is certainly important in view of what must be a limited supply of trained photographic imagery interpretive personnel. The development of sophisticated or quasi-sophisticated processing techniques is, in fact, not as forbidding as it looks. The statistical recognition techniques are elementary and are well known by most undergraduate scientific students today. The rather sophisticated remote sensing that we have been talking about is really nothing more than an extension of the aerial survey techniques which have such a long history in the field of development and resource

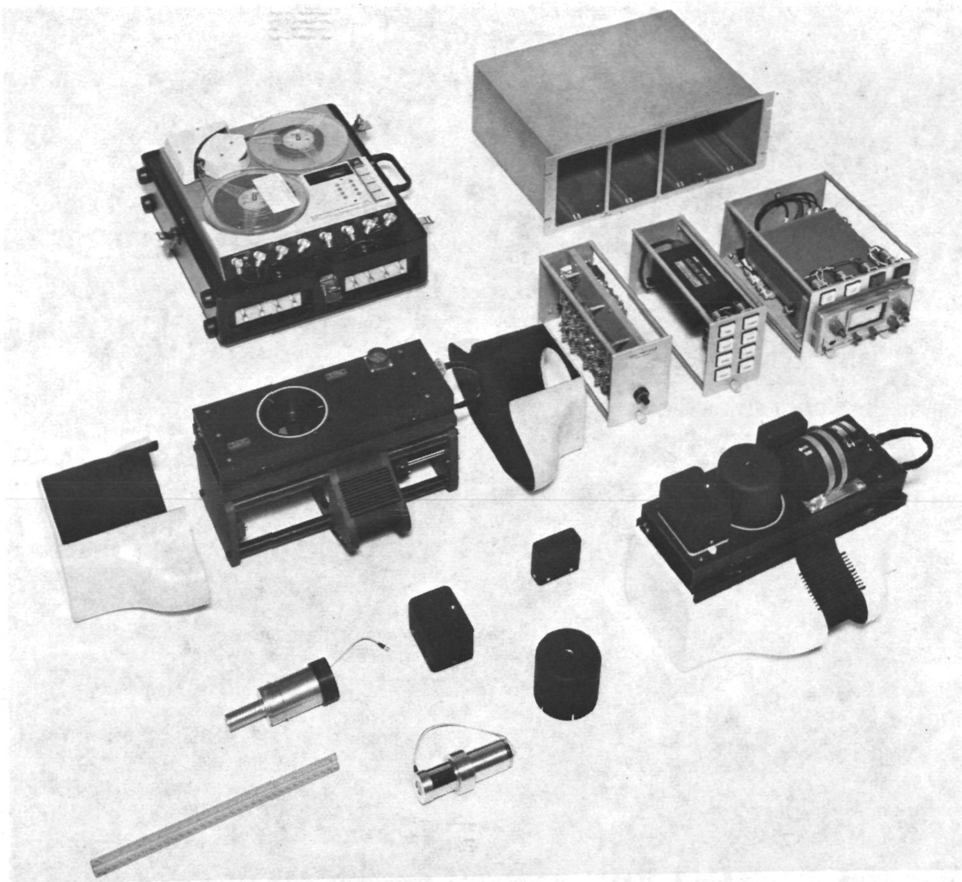

FIGURE 28. Daedalus line scanner and accessories.

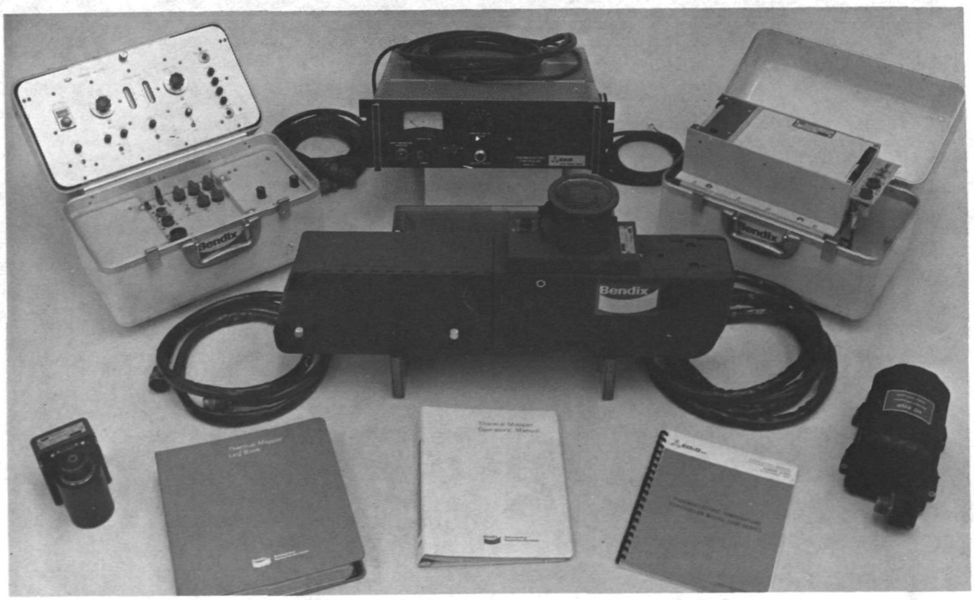

FIGURE 29. Bendix TM/LN-3 thermal mapper.

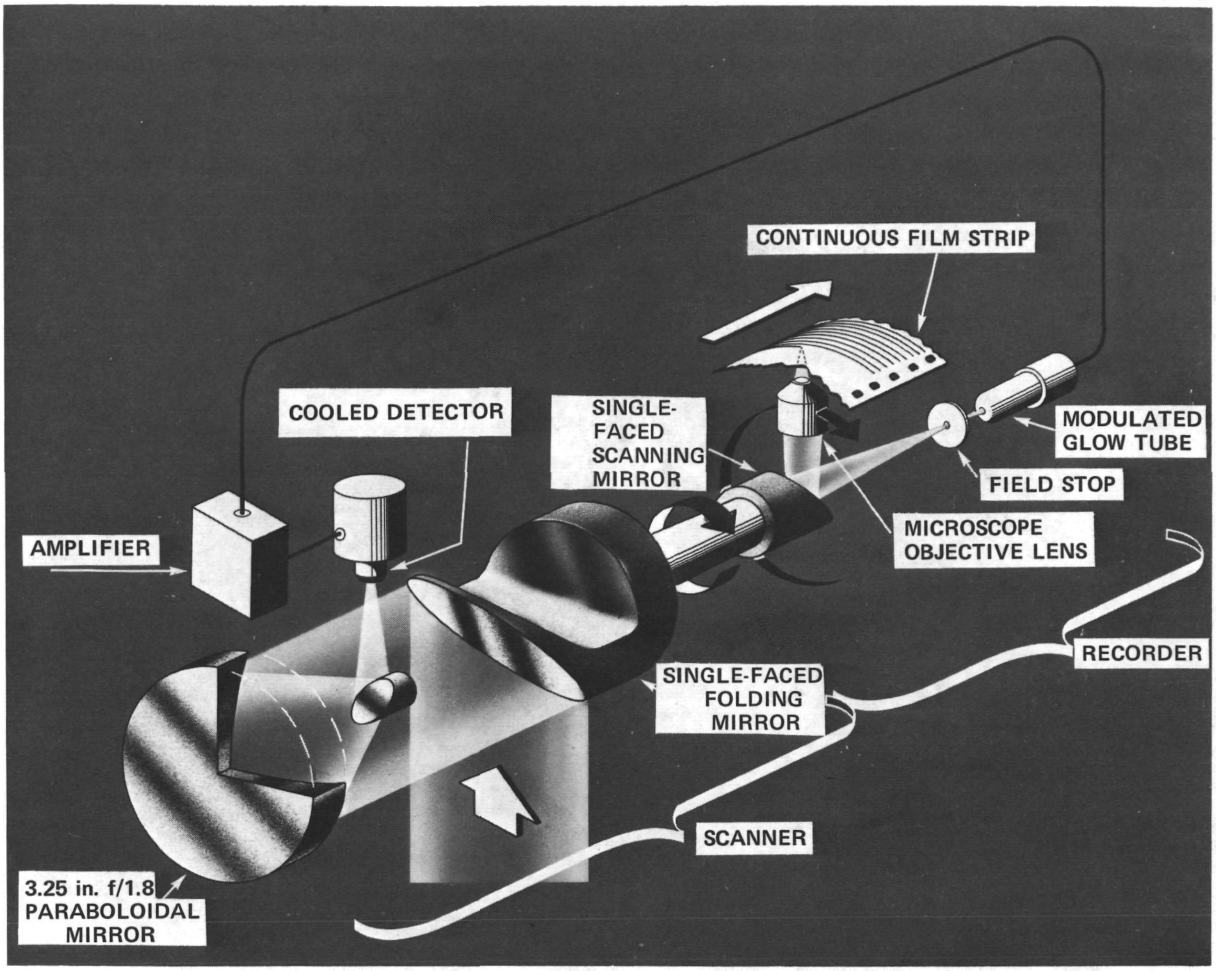

FIGURE 30. Optical configuration of Singer Reconofax IV.

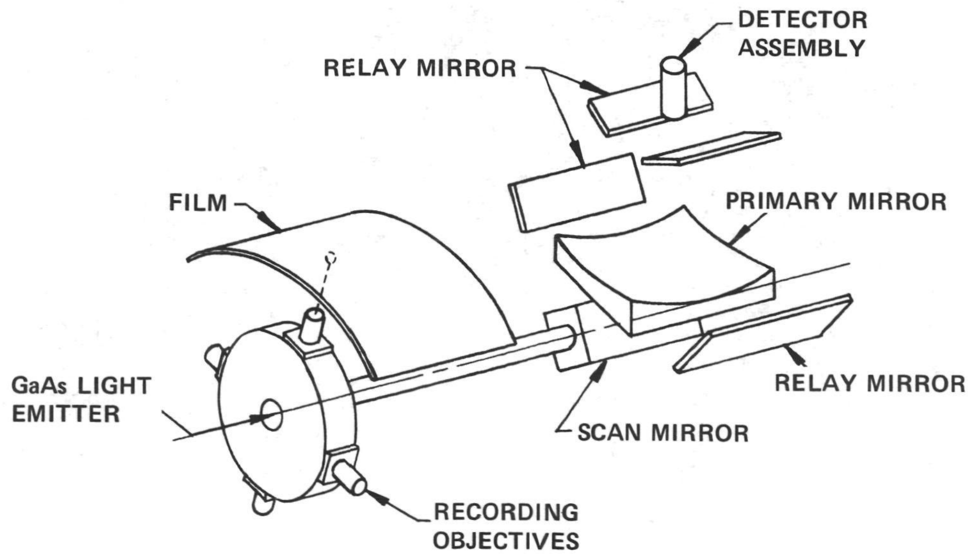

FIGURE 31. Optics diagram of Texas Instruments RS-310 system.

identification. It is an extension in two directions. First, it enables us to identify more objects, even with single-band imagery, than we were capable of with standard aerial survey systems. Second, and perhaps in the long run much more important, it gives us the capability to automate some of the more tedious jobs that we now present to the human interpreter. As a consequence, much larger areas of terrain can be covered in a much shorter time with fewer trained personnel. It is our opinion that in developing countries the use of automation, although it seems prohibitive initially, may in the long run be the best approach to the inventory resource studies that are so important in making plans for both administration and project development in these countries.

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SESSION IV

Chairman: Ervin L. Peterson

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Introductory Remarks

Ervin L. Peterson

Deputy Assistant Administrator for Technical Assistance
Agency for International Development

One purpose of this workshop, as I understand it, is to examine techniques, processes, and methods for identifying, locating, and measuring Earth resources in terms of their present usefulness and future potential. A considerable technology applicable to these purposes has developed in recent years; aerial photography, radar and magnetometer surveys, and infrared techniques are some of the areas explored. These methods have been used for topographic mapping, forestry surveys, mineral exploration, water resource evaluations, crop disease delimitation, and other purposes. They promise to save time, money, and effort. While these techniques do not replace detailed ground examination, they do serve to identify specific areas for such detailed investigations. We group these newer methods under the caption "remote sensing." Worldwide interest in remote sensing techniques is evidenced by the presence here of representatives from many countries.

Clearly, every country desires the development of its physical resources for their contribution to its growth and to providing a broader material base for improving the incomes and living conditions of its people. But each nation must first know what, where, and how extensive its resources are. The constraints of manpower and money command that efforts be directed toward the development of those resources most needed, best located, and with the greatest prospect of quick payoff. Conventional methods of resource location and delimitation are time consuming and costly. Remote sensing promises a rapid, less costly, and comprehensive means of identifying total resources and making selective detailed examination as a preliminary to full-scale development.

We are here today to consider ways and means of adapting this new methodology to the special needs and conditions of developing countries. With careful selection and application of presently available techniques and systems, growth and development for many, perhaps all, countries may be quickened, manpower and money for development more effectively used, jobs and employment more rapidly created, and the lives of people more quickly improved.

There are, as might be expected, some cautions which should temper our expectations. Remote sensing is a developing technology. It is sophisticated, requiring a high degree of skill in its operation; personnel must be competent and well trained in data accumulation, interpretation, and recording. Remote sensing does not yet eliminate the need for detailed ground investigation or ground verification of data secured by use of remote sensing techniques. Any system selected must be evaluated in terms of costs and benefits, operability, and usefulness of output.

Our session this afternoon was planned to address the economic aspects of Earth resources data acquisition and interpretation and to consider the role of small aircraft for survey purposes. Our speakers have both experience and expertise. We look to them for help in developing a broad perspective of the unique capabilities, constraints, and relative costs of various survey techniques.

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Some Criteria for Making Decisions to Invest in Resource Surveys, with Special Emphasis on Developing Countries

Kirk P. Rogers

Director, Office of Regional Development
Organization of American States

The new technology related to Earth resource surveys, which has been the stimulus for holding this workshop, clearly cannot be examined without considering the political, institutional, and economic frameworks in which it will be applied. My purpose is to contribute some ideas to the essential but difficult task of establishing sound criteria for investments in resource surveys.

I have chosen as the framework for my discussion the developing countries, not only because they are the focus of this workshop, but because decisions about investments in resource surveys are more critical for them. Developing countries financially can afford fewer mistakes. Their criteria for decisions must be clearer and sharper. Unwise investments in resource surveys that would hardly cause more than a ripple in the economy of the United States or a Western European country can have lasting and damaging effects on the economies of small, impoverished countries.

Having established the necessity of wise decision-making in dealing with this new technology in developing countries, I must hasten to add that our record to date has been very poor. Bad decisions about investments in resource surveys have been numerous, and wastes of human and financial resources have been great. If we are honest with ourselves, I think we must recognize that at this moment our knowledge of resource survey technology is far greater than our skill in using it efficiently in an economic sense.

We do not as yet have sound objective economic criteria for decisions about investments in resource surveys. We do not have decision models we can trust, nor have we perfected our cost-benefit criteria to apply to many forms of survey investments. Lacking these detailed criteria, however, we do have some general guidelines which have been derived from our experience and our mistakes. Having been a contributor to these mistakes through a decade of association with an international organization engaged in assisting developing countries, I feel qualified to discuss what we do and do not know about investing in resource surveys.

GENERAL ECONOMIC CONSIDERATIONS

The first and critical issue in making decisions is where to begin. I believe experience has taught us that we must begin with the demand for data. The basic question is not *how* are we going to get a particular kind of information, but what and why. Some of the worst mistakes of the past have been made because of preoccupation with means for collecting data—with aerial data collection systems, techniques for mapping, approaches to data analysis, data storage and retrieval, etc.—rather than the purpose of the data.

In a developing country, the major emphasis in collecting Earth resources data should be to provide a basis for development. I want to make it clear that I am in no way belittling the importance of basic scientific research, but I think we have to remind ourselves that developing countries with limited manpower and funds cannot afford the luxury of unfocused general-purpose data gathering.

The fact that new data collection technologies

have reduced costs means that we are able to do things which before were out of reach. As a result, it is now possible to gather quickly very large quantities of information, much more in fact than can be used. The possibilities of mismanagement are therefore greater. Decisions about resource survey programs should, more than ever, be made on the basis of actual data requirements for development objectives, rather than assuming that whatever is collected will eventually be useful. Decisions should therefore be based on a country's national goals and priorities for development, its projected rates of growth in different economic sectors, and its regional or spatial strategy for development. In short, a country should collect data needed to plan its development and execute specific development projects.

The goal should be a system whereby data collection programs are continually adjusted to demands created by private and public data-using entities. The extreme to be avoided is investment in resource development without data, but information collected without a clearly defined purpose is equally to be avoided.

Another basic reality is that resource data must be joined with other information to be useful for investment decisions. The procedure by which this is traditionally accomplished is the benefit-cost analysis. Economic potentials of natural resources are assessed by feeding physical, engineering, economic, and other data into a calculation of benefits and costs where the relationship between inputs and outputs can be examined. Our procedures are well established for benefit-cost analysis of projects involving direct use of physical resources such as irrigation projects, hydroelectric projects, colonization of new lands, etc. We know with some degree of certainty what type, quantity, and quality of data are required for these analyses. All development banks have such criteria and are constantly refining them.

Where we are weakest is in our criteria for general surveys prior to the identification of specific projects. Resource surveys at the reconnaissance level entail prospecting with high risks. If a survey is too intensive and we collect a lot of data but do not identify development possibilities, we may waste money. On the other hand, if our data collection is too superficial and promising opportunities are overlooked, we may retard development. It is exactly in this area of reconnaissance survey of physical resources that some of our new technologies using Earth resource satellites show greatest promise. If techniques can be perfected to carry out comprehensive reconnaissance surveys of physical resources in large areas at low costs, we will be solving one of the most critical problems we face today in countries beginning to develop their natural resources.

Before passing on to consider some noneconomic criteria for making decisions to invest in resource surveys, it is important to emphasize that countries at different levels of economic development have different data requirements. The whole discussion of resource survey criteria should really begin with a consideration of development level. The type, quality, and quantity of resource data needed by Paraguay (which is early in its development) is completely different from those needed by its next-door neighbors, Brazil and Argentina. A country's level of development frequently determines its capacity to finance data acquisition activities and utilize results.

GEOGRAPHIC CONSIDERATIONS

In addition to general economic considerations, a country's strategy for resource survey is influenced strongly by geographic factors. Among the most important are overall geographic size of the country, density and distribution of population, existing infrastructure, and spatial distribution of natural resources. A large, sparsely populated country with a uniform agricultural land base should adopt a different strategy than a small, densely populated country with limited agricultural resources concentrated in a few areas.

The intensity and timing of a survey are obviously affected by these geographic realities. The large country with the sparse population and the uniformly distributed resources, for example, may benefit more immediately from surveys utilizing satellite imagery, because it needs reconnaissance data for large land areas. The small, densely settled country may need detailed studies of limited areas, employing methods requiring much more ground truth.

I should mention in passing a critical geographic factor that is sometimes overlooked in the design

of resource surveys. The significant environmental differences between temperate and tropical zones are sometimes forgotten in the selection of technologies and methodologies. Since the majority of the developing countries are concentrated in tropical latitudes, this is an important consideration in any survey decision.

INSTITUTIONAL FACTORS

Critical to any decision about an investment in a resource survey in a developing country is a careful assessment of existing institutions and available trained manpower. Experience has shown that it is unwise to import large quantities of foreign expertise to do the whole job of data collection, because frequently all they leave behind is a handsome report and no one able to continue the analysis or effectively utilize the information. In effect, unless there is significant participation by the professionals of the developing country in data acquisition programs, the results may be wasted. The limiting factor is the capacity of the country to use foreign expertise to complement local capabilities.

Equally as important as trained local professionals is the development level of survey institutions. In many parts of the world, there are well trained professionals whose productivity is very low because they are not given adequate leadership and institutional support and because institutions are unstable. The limiting factor can indeed be the capacity of institutions, rather than the quantity and quality of trained individuals. Programs designed to build institutions as well as to collect data are needed.

In addition to capacities of institutions and individuals, a very important factor entering into decisions regarding resource surveys is the availability of existing data. After the economic needs have been identified and the country's institutional and professional limitations have been clearly identified, any plan for resource data acquisition should take full account of what data already exists. Surprisingly, many countries do not seem to know what data is already available and, in some cases, we see the tragedy of repeating survey work previously completed. In an inventory and cataloging of existing aerial photography and mapping carried out by the Organization of American States in Latin America in 1964–65, it was striking to note the number of cases of duplication of mapping by different agencies at different times. It was equally impressive to observe the very great extent to which Latin America had been photographed and the very small extent to which it had been mapped with photography. The limiting factor here did not appear to be the availability of imagery, but the capacities of the countries to analyze their imagery and convert it into data that could be utilized in making development decisions.

SOME CONCEPTS OF ENVIRONMENTAL DATA COLLECTION DERIVED FROM LATIN AMERICAN EXPERIENCE

Let me proceed now with the presentation of some general concepts for environmental data collection derived from OAS experience in Latin America, where I have been involved. These remarks should serve also to pull together some of the things I have said previously.

First, I would like to reiterate my belief that resource surveys in developing countries should be primarily development oriented and not scientific research oriented. I believe that resource survey programs should be developed in response to needs for data, as determined by national or regional economic plans for development, with identified goals and established priorities. In the case of Latin America, we have national economic planning boards which in the last decade have prepared economic development plans of varying duration with stated development goals and courses of action. Such plans and programs must be taken into account in developing programs for Earth resource surveys. Investments in data collection should be justifiable on the basis of overall development strategy.

Secondly, we should point out clearly that a resource survey is expensive, time consuming, and demanding in terms of the input of scarce professional talent. Data collection should not be open ended. Systematic inventories of physical resources for the acquisition of knowledge about the physical environment with no particular end in view are potentially wasteful in developing countries. An exception to this is a general reconnaissance overview of the environment intended to guide the formation of national development policies and focus

later investigations of physical resources in areas of high development potential. Every country needs some kind of a reconnaissance overview of its environment for intelligent development planning.

Our greatest concern is with open-ended resource surveys that involve systematic mapping at medium and large scales of large land areas, since a country needs a high level of development to afford this. We are also somewhat concerned with the involvement of technicians in some developing countries in basic remote sensing research. It is easy to attract first-class scientists in developing countries to this glamorous field, but we may in the process divert them from tasks of greater immediate importance to their countries.

Thirdly, our experience has shown that one of the most efficient ways to carry out development-oriented investigations is through a program which proceeds in phases. The broad overview of a large area known to be of development interest should be followed by more detailed investigations in limited areas with possibilities for specific projects. The final phase of investigation should then be a detailed study of physical factors involved in the economic and technical justification of a specific project. The main point here is that the minimum investment should be made in each phase before proceeding.

Scientists often want to extend work in their disciplines more than necessary because they want to produce the perfect geologic map or make a major contribution to the knowledge of soil science. It is difficult to restrain them, but it must be done because financial and human resources are scarce in developing countries.

Finally, experience has taught us that investigations of the physical environment should, as much as possible, be integrated and multidisciplinary in their approach. The objective is not only to economize on data collection and analysis by investigating several factors simultaneously, but more importantly to retain an overall view of the natural environment. What we are talking about here is basically the ecologic approach to resource survey. History is cluttered with examples of development failures which were also ecological disasters because projects were initiated without due regard for the dynamic equilibrium of the environment. The integrated approach of interdisciplinary teams will not protect us from all failures, but it will enhance chances for successful development with minimum damage.

In summary, we have said that data collection about the physical environment should be development oriented, integrated, and ideally proceed in a series of phases of increasing intensity from reconnaissance of large areas to detailed project studies. The data collection and analysis process should be continuous and orderly to yield specific developments.

We rarely achieve any goal without setbacks. Reconnaissance surveys indicating a need for more intense study in certain promising areas go unheeded while costly data ends up in sophisticated reports which cannot be used by decisionmakers. The interface between data producers, economists, and engineers who implement development is critical.

As we look ahead to the application of the new technologies for resource surveys in developing countries, we should constantly focus our attention on the critical need for an effective dialogue between data producers and users; it is this communication interface, rather than our ability to use technology, that I believe will determine our success or failure.

Benefit Analyses and Decision Models

M. Michael Gucovsky
United Nations Development Program

This paper is primarily concerned with decision models for choosing techniques and procedures to obtain information for investment decisions in the field of natural resources development (type A models). It will deal only briefly with decision models for improving the efficiency of managing existing resource systems (type B models). It will be noted that in some cases the two models could be combined, thus allowing significant economies in managing resource systems when developed. The information sought is defined by the stage in the decisionmaking process (i.e., general feasibility studies or engineering design) and by the characteristics of the resource system to be developed or to be efficiently managed. While most of the published studies are mainly concerned with improving the efficiency of managing already-developed resource systems, it is felt that more attention should be given to the type A models which may offer greater immediate advantages to developing countries.

TYPE A MODELS

The cost effectiveness criterion for choosing among alternative techniques and procedures will be supplemented by a time effectiveness criterion when it may not be feasible to estimate the economic loss function resulting from the need to postpone an investment decision due to the differing times required to obtain a given information mix. The characteristics of the new remote sensing techniques, whether airborne or spaceborne, offer economies of scale and of multiproduct operations. Consequently the project-oriented approach of much present information gathering will need to be replaced by information gathering procedures designed to meet the needs of a large number of complementary economic activities. Thus, in addition to obtaining greater cost effectiveness and time effectiveness in information gathering, it may be possible to obtain secondary benefits resulting from integrated planning of individual projects within one large region or within continguous areas. The above approach would indicate that more of the available R&D dollars could be devoted to developing cost functions for alternative systems of information gathering, as well as for developing optimal mixes of information units or points to be obtained from one data gathering system, which may consist of a combination of vectors on aircraft or spacecraft in conjunction with ground control. It will be noted that this analysis is quite simple and in most cases could be limited primarily to analyses of alternative costs alone. It is also stressed that this paper does not treat the general subject of the economics of information, or what constitutes valid information requirements for any given investment decision in a resources development scheme.

TYPE B MODELS

Decision models and benefit analyses for improving the efficiency of managing existing resource systems, which have been the subject of most of the studies undertaken directly by or for NASA, are dealt with only briefly. These models should center in the first instance on identifying ongoing data gathering activities on a global basis by international agencies and/or planned activities for the near future. The real costs of these activities should be adequately estimated so that they may serve as a

basis for comparing them with the cost of obtaining the same information through the application of spaceborne sensors. The models outlined *inter alia* in the Planning Research Corporation study and in the A. H. Muir and R. A. Summers paper No. 68–1077 (AIAA Fifth Annual Meeting, October 21–24, 1968) and in Summers' paper presented to the Sixth Annual Symposium on Remote Sensing of Environment, October 13–16, 1969, serve as a basic theoretical framework for this purpose.

SESSION V

Chairman: Herman Pollack

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Introductory Remarks

HERMAN POLLACK

Director, Bureau of International Scientific and Technological Affairs, Department of State

In his annual report on foreign policy issued just over two months ago, President Nixon stated, "Space is the clearest example of the necessity for international scientific cooperation and the benefits that accrue from it. The world community has already determined and agreed that space is open to all and can be made the special province of none. Space is the new frontier of man, both a physical and an intellectual frontier."

This workshop, which has come into being as an earnest of President Nixon's wish to share the benefits of our remote sensing program with the rest of the world, will demonstrate the potential of this new technological tool and how it can be used for man's benefit. I wish to stress at the beginning that, if remote sensing is to live up to its great promise, it depends on close international cooperation and a widespread recognition that we have important resources in common. Let me illustrate how the State Department and my Government see this program.

Important tasks confronting our own country require information developed on a broad and in some respects global basis. This is clearly so, for example, in the case of environmental, oceanographic, and resource problems which transcend national boundaries. To meet our own needs, we must conduct the program on a basis which will merit international acceptance.

We cannot insure our own welfare in isolation; we must find ways to enable other countries to participate in and contribute to this program. We must also look for ways of relating our own work to comparable efforts of other countries, as we have already done with Brazil, Mexico, and Canada. Let me also cite the recent understanding between NASA and the Soviet Academy of Sciences to consider techniques for studying the natural environment.

We have been and will remain mindful of the special needs of developing countries. We must seek ways of relating this program's potential contribution to those needs.

As our understanding of common problems develops, we may see the tasks confronting the world community in a new perspective. And as new opportunities for joint action emerge, we must try to exploit them. For example, such joint action will be imperative in dealing with international or inadvertent modification of the environment. Therefore, we feel we must be prepared to seek international cooperation in putting to work the information resulting from this program, so that common understanding of our shared problems may be deepened and mutually beneficial approaches developed.

I am honored to be the chairman of this session, in which we shall hear descriptions of other countries' programs.

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Brazilian Program for Remote Sensing of Earth Resources (Project Sere)

João Botelho Machado

Comissão Nacional de Atividades Espaciais (CNAE)

This report presents a description of the Remote Sensing of Earth Resources Program being implemented in Brazil. Emphasis is on the main features of the program. Possible future repercussions of trends becoming apparent are also discussed.

Because of the way the program is being developed, we could not avoid an almost purely descriptive presentation. Therefore, in only a few cases are operational aspects supplemented by specific data which we hope will reflect as faithfully as possible our program's features and problems.

Obviously, our program concept, contents, aims, and methods were determined by our country's social and economic system, level of development, geographical extension and situation, scientific and technological potential, and national traditions in various spheres (such as higher education, scientific research, industry, etc.).

STRUCTURE

Among the main reasons for the complexity of our program are the increasing need for the exploration and exploitation of vast unknown regions, the magnitude of required human and financial resources (which made government action and support a basic responsibility), the limitations of available resources (which obliged coordinating authorities to determine options and establish priorities), the increasing extent of international cooperation in science and technology, and the varied nature of our objectives.

The agency selected by the Brazilian Government to implement and coordinate our Remote Sensing of Earth Resources Program is a space science and technology oriented institution known as Comissão Nacional de Atividades Espaciais (CNAE) and linked to the National Research Council, a governmental body that coordinates national research activities and reports directly to our President.

Plans established for CNAE cover the period of 1969 to 1973. They permit growth compatible with the country's financial potential and are based on a realistic appraisal of industrial development as well as the qualifications of Brazilian scientists and technicians.

The CNAE will soon be renamed Instituto de Pesquisas Espaciais (INPE). It has its headquarters at São José dos Campos, State of São Paulo, and it is the only civilian institution exclusively dedicated to space science and technology in Brazil. It also coordinates space activities of other groups.

Since its creation, CNAE has closely cooperated with NASA. This cooperation has helped put Brazil in a position comparable to that of other scientifically advanced nations.

Early in 1966, NASA suggested CNAE participation in a cooperative remote sensing project for an aerial survey of selected areas to be used as "lunar analogs." This project was soon abandoned, but it resulted in another program associating Brazilian and United States groups in the development of techniques and systems for interpreting and utilizing Earth resources data collected by aircraft and in determining the potential use of spacecraft for the same purpose.

This cooperative program began in 1968 with a 6-month training period for 12 Brazilian scientists in the United States. In 1969, after the development

of five Brazilian test sites in cooperation with local user agencies, overflights in Brazil helped us evolve an optional configuration for our own aircraft sensor system.

In October 1970, a meeting with NASA representatives was held at our institution's main center for the formal presentation of final reports on the third phase of the NASA-CNAE cooperative program.

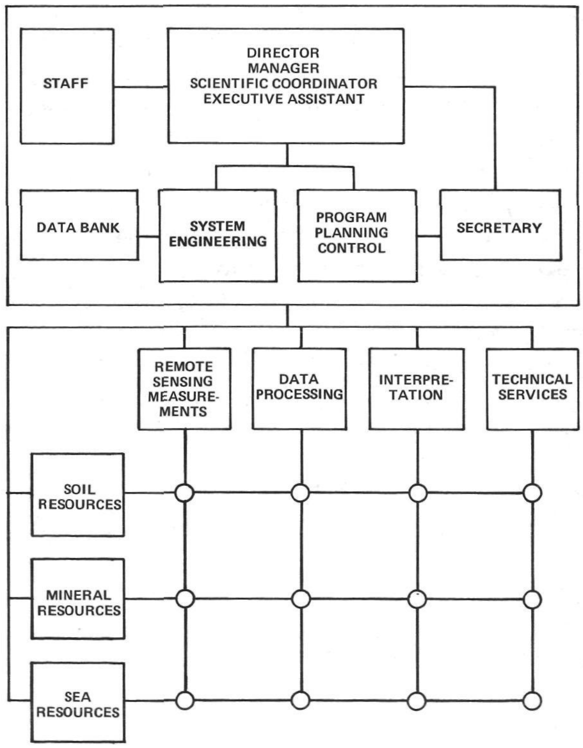
Our CNAE operational flights, which constitute the fourth phase of the program, will start soon with a Brazilian-built aircraft which is in the process of being instrumented.

Experience obtained during the preparatory phases of the NASA-CNAE mission necessitated a fundamental change in our approach. For example, there were extreme differences in pace of work done at our user agencies due to the lack of internal support received by some principal investigators (not a lack of financial resources). One source of this difficulty was the manner of presentation of the project to prospective users. Too often, an initial proposal concerning remote sensing is so appealing that expected results are easily overestimated. Thus, in certain groups, motivation faded rapidly with the first minor difficulty, while early successes in other groups created an enthusiastic attitude which led to extensive aerial surveys with available equipment. The most realistic positions were assumed by investigators with a clear understanding of their sensor capabilities and the significance of the sensed data, as in the case of remotely measured sea-surface temperatures for oceanographers.

In the beginning of our program, a one-way flow of simple support was established—from the data collecting and processing activity to the data interpretation personnel. The supporting activity ended when carefully collected and processed data were delivered in the manner specified by each investigator. We are trying to remedy this situation by establishing a specific objective-motivated type of operation.

Thus, our in-house discipline interface groups (comprising numerous well qualified specialists in natural and cultural Earth resources working in close relationship with our instrumentation, flight operations, data processing, and data bank groups) try to maintain adequate channels for an exchange of ideas on progress and program development between Brazilian user agencies, our own organization, and foreign counterparts. They also report problems in user areas. In this closed-loop system we expect to have resource-minded, instrument-acquainted, in-house people—not just instrumentation experts providing subsystems of data collection. To keep the system working smoothly, we will have an internal system analysis group in charge of project planning and control.

To assure adaptability and flexibility in dealing with the frequently changing objectives of subprojects, a matrix type of organization chart is used by our project. This type of organization (see figure) enables a well established set of functional groups to support different subprojects being developed. In other words, the functional groups provide personnel for active subprojects and support to their scientists.



Matrix organization chart for remote sensing project.

Ongoing subprojects in a matrix organizational chart may be shown graphically as groups of scientists, horizontally alined by specific subprojects, located vertically under functional groups. Additional subprojects may be easily added and, as com-

pleted or phased-out subprojects are excluded from any organization, personnel are returned to their original functional groups.

HUMAN RESOURCES

For the development of a program, our institution requires highly skilled scientists and technicians in significant quantities. Due to a lack of remote sensing educational centers in Brazil, it was necessary for CNAE to develop its own courses with the help of specialists trained in the United States.

At the moment, we have the following groups of specialists working on our project:

Agronomists	13	Discipline group = 25
Geologists	8	
Oceanographers	3	
Geographer	1	
Electrical engineers	5	Data collecting group = 13
Electronic engineers	2	
Physicists	2	
Pilots	2	
Aerophotogrammetrists	2	
System analysts	3	
Librarian	1	
Secretaries	2	Total = 44

The project will be fully operational when the Bandeirante PP–ZCN remote sensing aircraft is in routine use, probably by June 1971. Meanwhile, discipline specialists are still working with data collected during NASA aircraft overflights in Brazil in close contact with user agencies.

Supporting groups are working on such interpretation technique developments as:

- Analysis or digital information extraction techniques.
- Decision-oriented resources and environmental models, including numerical prediction models (e.g., river basin models), conceptual system models (e.g., epidemiological models), management models (e.g., relevant enterprise models), multistage sampling models (e.g., statistical inventories), temporal models (e.g., crop calendars), and statistical classification models.
- Sensor technology work involving such numerical parameters as sensitivity, resolution, signal-to-noise, error, and degradation.

In cooperation with the Brazilian Coffee Institute, data collected by private aircraft is being used for coffee planations hit by frost, infested by nematodes, and infected by coffee leaf rust. In this work, only photographic sensors are employed, using color Ektachrome and false-color IR Ektachrome films.

In addition, CNAE maintains agreements with the following Brazilian Government agencies which have their own investigators:

- The Ministry of Mining and Energy through its Departments of Mineral Production and Water and Electrical Energy
- The Ministry of Agriculture through the Office of Research and Experimentation
- The Ministry of Trade and Industry through its Brazilian Coffee Institute
- The Ministry of the Navy through its Hydrographic Office
- The São Paulo State Secretary for Agriculture through the Agronomic Research Institute of Campinas and the Institute of Agronomical Economy
- The University of São Paulo through its Oceanographic Institute and the Institute of Geophysics

We are trying to implement and operate a system of the highest quality compatible with the available talent. All efforts are being made to recruit young graduates from higher-level Brazilian colleges.

Young scientists and engineers usually change jobs more frequently than older ones. Some start working in a relevant branch of industry and move to research, while many others move in the opposite direction, especially in a developing country. CNAE definitely needs more experienced people for key positions, but experienced scientists and engineers are reluctant to move to other jobs if this means relinquishing stable career prospects.

MATERIAL RESOURCES

Budgetary Resources

The annual budget of our institution is supplied through the National Research Council. For the current fiscal year, it totals about $7 million.

The National Development Bank, through the

Technological and Scientific Fund, cooperated in the development of our project by providing the equipment now in use or being installed on our aircraft. The aircraft itself was bought with resources from our own budget.

CNAE Aircraft

The Bandeirante PP–ZCN is a two-engine, low-wing aircraft modified to carry passive sensor equipment. It operates from small airfields, has a maximum takeoff weight of 5100 kg, and is powered by two turboprop engines. It requires a crew of two pilots, one flight director, and two sensor operators. It was designed and built by the Embraer Company at São José dos Campos. Its performance characteristics include:

- Maximum altitude: 8.5 km
- Airspeeds: 418 km/h (cruising); 510 km/h (max)
- Payload: 1800 kg
- Range (at 3 km alt.): 1850 km

In addition, the aircraft is equipped with:

- Wild RC–10 metric camera
- Hasselblad 500 EL/70 four-camera cluster
- Bendix LN–3 thermal mapper (two channels, one thermal)
- Barnes PRT–5 precision radiation thermometer
- Ampex AR–1600 magnetic tape recorder
- Bendix DRA–12 Doppler radar
- Bendix AN/APN 184 radar altimeter
- Bendix M–4C automatic pilot

Photographic Laboratory

The CNAE photographic lab has a basic capacity for:

- Automatic black-and-white film processing up to 24 cm wide
- Semiautomatic color film processing up to 24 cm wide
- Log Etronic printing up to 24 cm wide
- Color and black-and-white enlargements

Analog/Digital Data Conversion Equipment

CNAE computer facilities include:

- HP 2116 B computer (16K-word memory)
- Teleprinter
- Paper punch reader
- Tape punch
- Magnetic tape units (2)
- HP 2311C ADC subsystem with Walthom 56 IDA
- HP 2791A pacer for high-speed data acquisition

FUTURE DEVELOPMENTS

Three proposals were forwarded to the NASA Office of International Affairs for investigations using data from the first Earth resources satellite as part of the fourth phase of the plan of cooperation between Brazil and the United States for applications of remote sensing.

Our own in-house proposals cover the following disciplines:

- Agriculture, forest, and grassland studies of the viability of scientific uses and economic substitutions for conventional methods of surveying natural and cultural resources
- A geological study of remote sensing applications
- An oceanography study to develop a new bathymetric technique

In addition, two other proposals have been prepared by two cooperating agencies—namely, the Ministry of Mines and Energy and the Brazilian Coffee Institute of the Ministry of Trade and Industry. The first was "A Proposal for the Application of ERTS-A Data to Resources Analysis of the Amazon Basin" and the second was "Experimentation to Verify the Viability of Orbital Image Interpretation of the Physical Aspects of Brazilian Coffee."

In the latter proposals, user agencies are seeking a research program to supplement two present ongoing aircraft projects—namely, the Ministry of Mines and Energy RADAM Project and the Bra-

zilian Coffee Institute Photointerpretation Service Project. The first is a multidisciplinary project based on complete aircraft coverage of part of the Amazon region (1 500 000 km^2) to obtain data with synthetic-aperture SLAR in conjunction with limited amounts of multiband aerial photography from high and low altitudes and ground truth to map mineral, vegetation, soil, and water resources. The flights are scheduled to start in June 1971 and should be finished in four months.

The second project is an agriculture project dealing with coffee resource management (inventory, yield prediction, etc.). In both cases, there will be correlative data to permit analysis of data from satellite experiments in short periods of time.

Our institution will coordinate and work with the user teams, and will provide support in the following activities:

- Aircraft underflight
- Photographic processing
- Data analysis and information extraction such as densitometry, multispectral projections, and computer processing
- Data receiving, storing, retrieval, and distribution

Our in-house proposal, besides having specific scientific objectives, aims to keep updating our investigators' competence to solve problems arising from a rapidly evolving technology.

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Remote Sensing in the Economic Management of Coffee Production and Marketing

MARCOS H. VELLOSO

Comissão Nacional de Atividades Espaciais (CNAE)

Experimentation was completed to test the viability of color Ektachrome and IR Ektachrome aerial films in the detection of different degrees of defoliation in a coffee crop following a severe frost attack. The relationship between defoliation and production recovery is described. The logic of a program for automatic analysis and mapping of frost damage is outlined and its use in production prediction is described.

In the normal input/output situation for an agricultural economy, inputs usually reflect production levels fairly well. However, in the case of coffee production in Brazil, much of the crop is concentrated in the States of Paraná and the southwestern part of São Paulo State. Both regions suffer from frequent frost attacks. Occasionally, water deficiency also affects production levels. During such periods, the accuracy and timeliness of production prediction become more difficult because production levels bear little relationship to the variable inputs of the aggregate production function for coffee. The production levels are more strongly related to the broad geographical locations of the coffee regions and to frost distribution within those regions. Hence, statistics on the extent and degree of frost damage are important inputs to an operational production prediction system which, under normal circumstances, operates on conventional input/output systems of production prediction.

DEVELOPMENT OF A MODEL FOR PRODUCTION

The recovery in production of a crop defoliated by frost is, in general terms, related to the remaining live leaf area on each bush and follows the well known profile of the logistic curve of growth (figure 1).

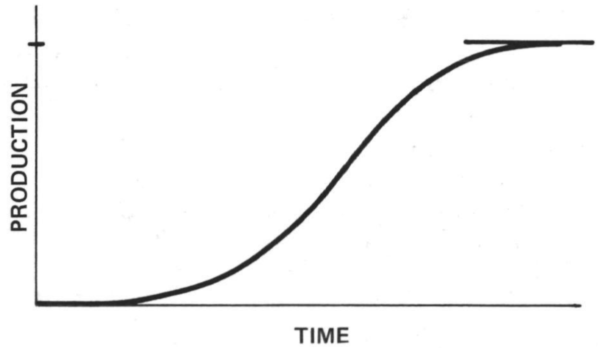

FIGURE 1. Logistic growth curve for recovery of production.

The development of a survey system to indicate live leaf areas for a crop should permit the collection of the following useful information:

(1) Estimation of location of frost damage.

(2) Estimation of production recovery profile based on estimates of differing degrees of frost damage.

Theoretically, the effect of frost is to shift production levels down on the aggregate production function as shown in figure 2. The recovery period is related to the degree and extent of frost damage and is represented by period RP. The advent of frosts during the recovery period has no effect on the utility of the model, since each frost simply shifts

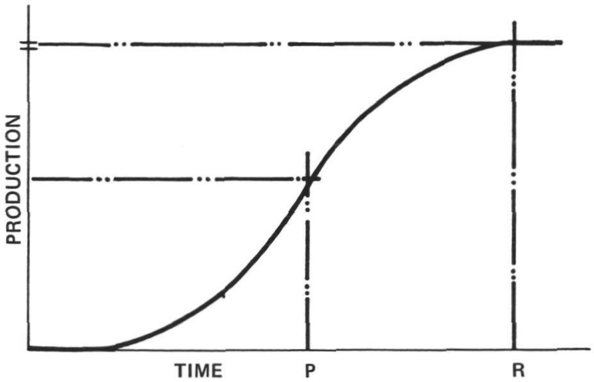

FIGURE 2. Depression in production following frost attack.

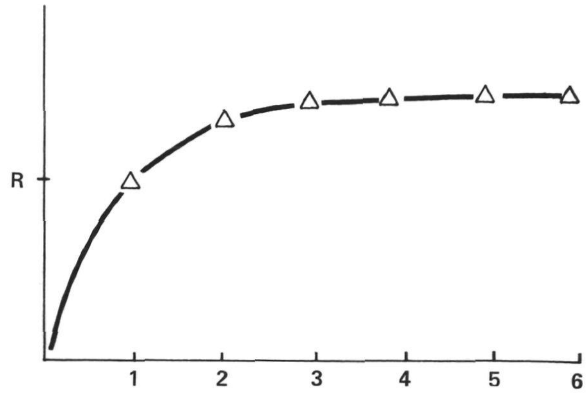

FIGURE 3. Relationship between diffuse reflectance and leaf area index (LAI).

the production point further down on the aggregate production function.

Recovery of the coffee crop from a frost attack is related to the remaining leaf area indices (LAI) of the individual trees. Work by Myers *et al.* has indicated the relationship between LAI and the diffuse reflectance of plants of radiation in the 0.75-to-1.5-μm region. Such reflectance is related directly to the LAI through a function of diminishing marginal reflectance (registered by the sensor concerned).

According to Myers' results, we conclude that the function relating reflectance to LAI is of the following series form:

LAI	*Diffuse reflectance*
1	$R.$
2	$R + (0.3)R.$
3	$R + (0.3)R + (0.3)^2R.$
4	$R + (0.3)R + (0.3)^2R + (0.3)^3R.$
5	$R + (0.3)R + \ldots + (0.3)^4R.$
6	$R + (0.3)R + \ldots + (0.3)^5R.$

Graphically, the function takes the form shown in figure 3. As can be seen, the differences in diffuse reflectance between LAI = 4, 5, and 6 are almost negligible. Hence, useful differentiation of LAI is possible only within the range LAI = 0 to LAI = 4.

METHODOLOGY

Use was made of color Ektachrome and infrared Ektachrome films as well as a PRT–5 sensor. Flights were made at altitudes providing scales of 1:6000, 1:15 000, and 1:25 000. Both types of film were exposed at 1/300 second at f/5.6, with the IR film exposed through a Wratten 15 filter.

A simple numerical scale, developed for field workers who surveyed the test site, is illustrated in figure 4. It measures the degree of frost defoliation.

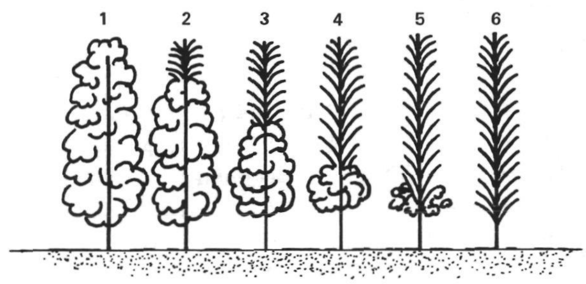

FIGURE 4. Defoliation scale for field survey.

Field data was also collected on interrow crops, coffee tree spacing, variety, and age. Temperature measurements were made of soil and leaf surfaces, and meteorological conditions were recorded before and after each flight.

ANALYSIS OF THE DATA

Analysis of the data was based on photocopying techniques using different filter overlays on transparencies of color and color IR. The aim of the photocopying techniques was to delineate broad boundaries between different degrees of frost attack for these reasons:

- It makes little sense to carry out individual tree readings in imagery for a statistics

collection system to be applied to thousands of square kilometers of terrain.

- By using broader classifications for frost damage, it is simpler to develop pattern recognition programs for automatic analysis and a direct input into the production prediction model.

Each photocopy frost boundary was plotted by hand on an acrylic screen to test the viability of the aerial data in locating crop conditions recorded on the ground in accordance with the numerical scale. The aerial data correlated well with the data from the field, and the best results were obtained from filtered photocopies of the color IR Ektachrome film.

Since the photocopying methods delineate boundaries of broad areas, we are essentially dealing with leaf areas on a field scale rather than a per-tree scale.

AUTOMATIC DATA ANALYSIS FOR MAPPING FROST DAMAGE AND ESTIMATING PRODUCTION

Several suitable pattern recognition programs can plot boundaries between differing target variables in photoimages.

Sakai *et al.* have developed an operational program for frontier detection which they used for face recognition in photographs digitized with scanners. The scanner produced a matrix of density levels, which were separated through computation into line segments following the points of greatest gradient between successive points in the matrix.

Sakai *et al.* also took into account the eight points surrounding any matrix point (figure 5). Each point has a specific gray level, and the direction and value of maximum gradient from the point was marked in the printout. This type of program is ideal for imagery of great homogeneity. For

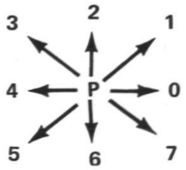

FIGURE 5. Matrix point and surrounding points considered in digital recognition system.

natural vegetation, crops, and related phenomena, great homogeneity is seldom encountered, however, and a program which plots gradients for each matrix point would be too noisy.

McNeill has developed the logic for a program which overcomes the problem of noise in such phenomena as crops and natural vegetation. The program is simple and utilizes single scan lines of the digitizing apparatus (optical density, TV, etc.).

Consider the digital gray level estimates shown in figure 6 for a single scan across a photographic image. To suppress noise in zones with mean densities of specific values, moving averages of gray level readings are taken in duals, triplets, etc. The number for estimating the moving average is proportional to the variance and frequency encountered.

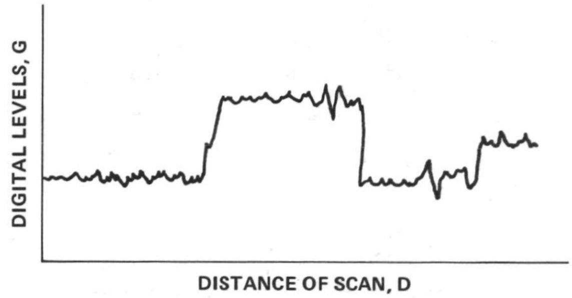

FIGURE 6. Digital gray level scan.

The new profile is then converted into a gradient profile which estimates the rate of image density change with respect to the distance along the individual scan line (figure 7). The gradient is equal to dG/dD, where G is the gray level and D is the distance.

The dG/dD values are plotted in sequence and the threshold level is set for the computer to select those dG/dD points which exceed a specific value. Where the dG/dD transform value exceeds or is equal to the threshold level, the program records a mark for a boundary as shown in figure 8.

Altering the threshold values also changes the number of boundaries recorded (figure 9). The program requires a loop to select the correct threshold for specific crop conditions on each photocopy. Figure 10 shows an example of a printout based on analysis of several photocopies.

Obviously, this form of conversion can be made

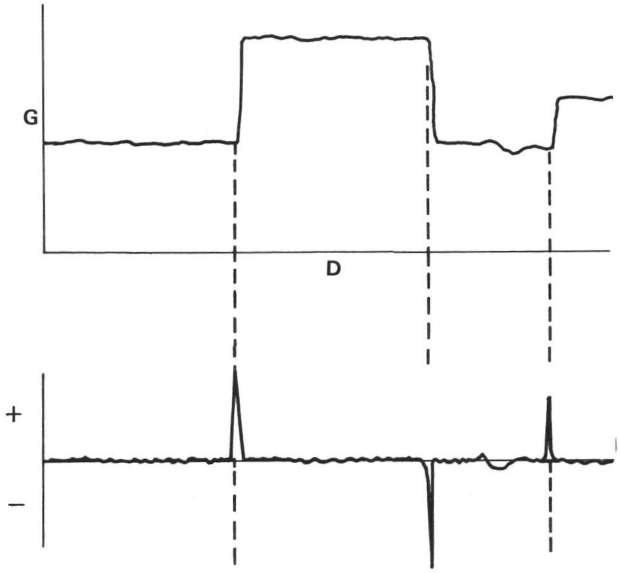

FIGURE 7. Corrected profile (top) of scan shown in figure 6 and dG/dD transform (bottom).

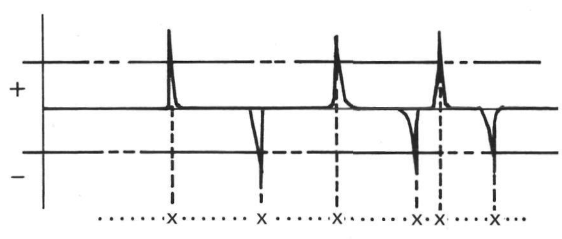

FIGURE 8. Boundary marks (x) recorded for single threshold.

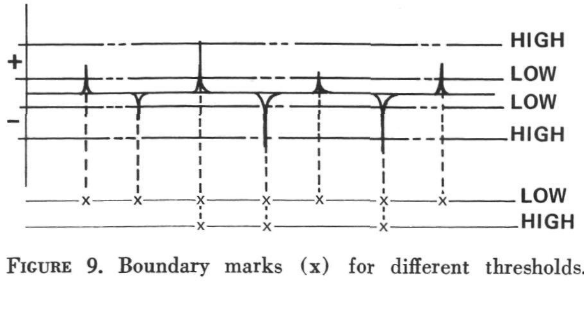

FIGURE 9. Boundary marks (x) for different thresholds.

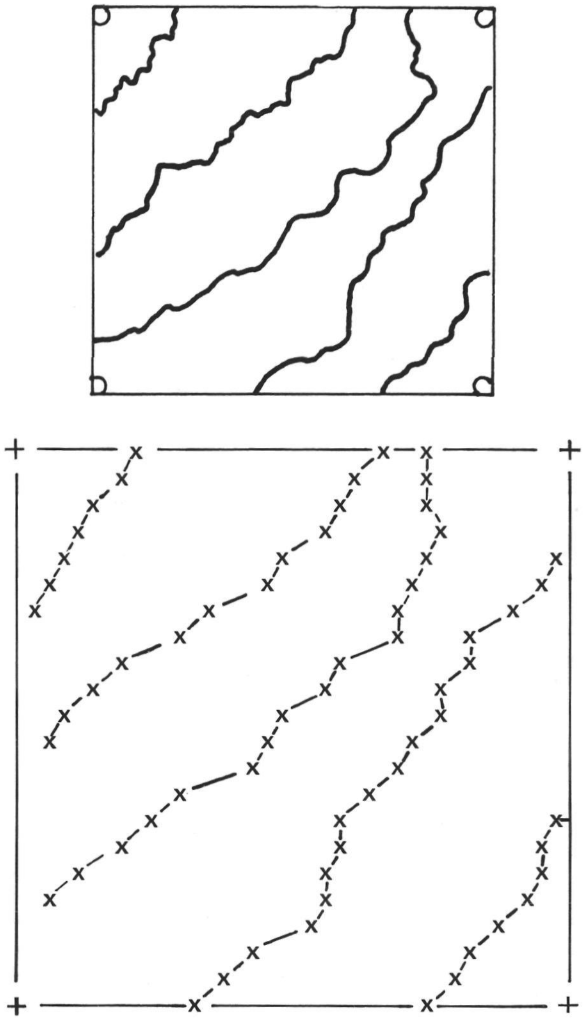

FIGURE 10. Image (top) and printout (bottom).

more simply on the basis of vidicon conversion using different contrast levels on differently filtered transparencies. The program described above is an example of a simple program for use in the absence of such equipment as a vidicon.

DIRECT INPUT SYSTEM FOR MODEL

Following is an example of the application of information gained from the frontier program. Assume that, on the basis of the numerical field scale (1 to 6), we have the following distribution for a specific region:

Scale class	*Percent of coffee in region*
1	30
2	10
3	15
4	20
5	15
6	10
7 (new plantings)	10

From agronomic records, let us assume that the general recovery pattern for the seven categories is as follows:

Scale class	*Percentage of prefrost harvest*
1	100 at next harvest.
2	80 at next harvest and 100 at 2nd.
3	50 at next harvest, 80 at 2nd, 100 at 3rd.
4	35 at next harvest, 50 at 2nd, 80 at 3rd, 100 at 4th.
5	10 at next harvest, 35 at 2nd, 50 at 3rd, . . . 100 at 5th.
6	No recovery
7	10 at next harvest, . . . 100 at 5th.

Hence, production recovery is as shown in the table below.

The graph shown in figure 11 illustrates the production recovery profile related to the hypothetical data in the table. Both production deficit and recovery rate can be calculated from the data. Each class of defoliated tree recovers from a different point on the logistic curve and, for each year, the production is weighted for each class of damage.

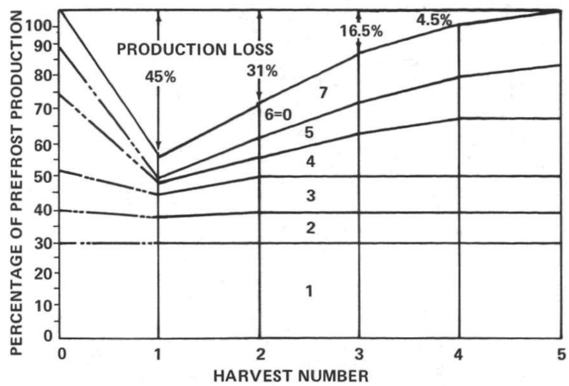

FIGURE 11. Production recovery profile for seven classes of frost damage.

Data is currently being collected on the test site to construct a recovery profile for each class of frost damage. This data collection should be completed by 1974.

Once agronomic information has been collected on specific recovery profiles for different degrees of frost damage, the boundary recognition program can automatically produce the weighted recovery production profile.

PRT–5 DATA RESULTS FOR THERMAL REGION

The PRT–5 data (line transect for 8-to-14-μm band) correlated well with temperatures recorded on the ground. However, variations of thermal readings with meteorological conditions and time of day (water regime of soil and plants and microthermal regime) limit the thermal region in the detection of frosted regions. It is true that, in general, defoliation causes greater soil exposure, resulting in higher temperatures recorded by the PRT–5.

Harvest following frost	Defoliation scale class							Total aggregate
	1	2	3	4	5	6	7	
1st	30	8	7.5	7	1.5	0	1	55%
2nd	30	10	12	10	3.5	0	3.5	69%
3rd	30	10	15	16	7.5	0	5	83.5%
4th	30	10	15	20	12.5	0	8	95.5%
5th	30	10	15	20	15	0	10	100%

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The Use of Remote Sensing in the Detection of Coffee Leaf Rust *(Hemileia vastatrix)*

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Preliminary work was carried out in the detection of *Hemileia* in coffee using color Ektachrome and IR Ektachrome films. Work methodology is described, and the form of analysis is outlined. Results indicate that considerable thought should be given to the use of haze filters for high-altitude color photographic work. Also, based on successful ground shots with IR Ektachrome, it was concluded that the aerial IR exposures are critical. To insure optimal exposures in the future, a tethered balloon system has been developed for preflight testing of film at low cost.

The discovery of *Hemileia vastatrix* in the Brazilian coffee crop in January 1970 presented an opportunity to test applications of remote sensors in locating different degrees of infection.

PROPOSED USE OF INFORMATION

Agrometeorological records indicate regional susceptibility to coffee leaf rust. The aim of a dynamic location system is to alert authorities when the disease is spreading to particularly susceptible regions, thus enabling actions to minimize the effects on annual production and permit relatively smooth transitions in production. The main advantage of remote sensing techniques is in the use of previsual signals of the disease using the near IR region of the electromagnetic spectrum.

METHODOLOGY

The following field data were collected on a test site near Caratinga, Minas Gerais:

- Presence or absence of *Hemileia*, + or —
- Percentage area of individual leaves covered with *Hemileia*, h_1
- Percentage of leaves of tree affected with *Hemileia*, h_2
- Color of *Hemileia* infestation, c_h
- Color of leaves in general (disease free), c_b
- Percentage area of individual leaves covered with other diseases, o_1
- Percentage of leaves of tree affected with other diseases, o_2
- Color of other disease infestation, c_o
- Leaf loss of the tree, d

An 11-percent survey methodology was applied in sampling individual coffee trees in the test site.

AERIAL DATA

Aerial photographs were made using color Ektachrome and IR Ektachrome films. In addition, 35-mm IR Ektachrome film was used with various filters. Flights were made at altitudes providing scales of 1:2000, 1:4000, 1:6000, 1:8000, 1:10 000, 1:15 000, 1:20 000, and 1:25 000. Various exposures were made at each altitude.

ANALYSIS

The analysis was based on comparison of the imagery with test site maps produced by plotting

h_1, h_2, c_b, c_b, c_o, and d obtained from field survey work. Because of the mountainous nature of the test site, the whole site was mapped on the basis of aspect and slope. For statistical analysis of the imagery, only regions of the same aspect, slope, variety, age, and spacing of trees were compared.

RESULTS

The color scale developed for the study proved to be very effective in predicting usefulness of color Ektachrome film for discriminating separate visual color effects in foliage. Ideal scales for the detection of *Hemileia* with color Ektachrome were tentatively estimated to be 1:6000 to 1:8000 (requiring an altitude of about 1 km). However, minus-blue filtered 35-mm color Ektachrome photographs indicated that optimal altitude could be increased appreciably through the use of minus-blue filters, such as the Kodak HF series. Future tests will include the selection of HF filters for higher-altitude flights.

IR Ektachrome film proved to be ineffective for disease detection work, although copying methods with blue light showed up nutrient deficiency symptoms in the crop very well. Ground shots made with new IR Ektachrome film demonstrated that *Hemileia* shows up well in film relatively underexposed in the IR band. It was concluded that the balance in sensitivity of the IR 8443 film bands for green, red, and IR should be altered to suppress IR sensitivity in order to obtain useful images for repetitive disease detection work.

To insure correct aerial IR exposures in the future, a small tethered balloon system has been developed as a low-cost method of determining optimum exposures for the lowest flight altitudes (300 meters). Bracketed exposures will be used at higher altitudes. We are confident that, with these precautions, the next flight test will prove successful in the positive detection of *Hemileia* from the air.

Some Practical Results of Remote Sensing Over Test Site 701, El Oro-Tlalpujahua, Mexico

Carlos Acosta Del Campo

Consulting Geologist, Consejo de Recursos Naturales No Renovables, Secretaría del Patrimonio Nacional

A comparison of imagery gathered by several remote sensors over Test Site 701, El Oro-Tlalpujahua, showed the superiority of infrared or false-color film over color, panchromatic black-and-white, and infrared black-and-white photographic emulsions in terms of reliability, economy, and speed for economic geology.

Our study of thermal imagery is still in progress, but such imagery appears to have only a few applications to economic geology in restricted, specifically oriented investigations. Radar imagery presented small scale, poor ground resolution, lack of contrast, and heavy graininess; but it was quite useful in tectonic studies and should therefore be helpful in investigations of economic geology. Radar imagery furnished confirmation of a suspected fault system; and, in this respect, it was far superior to all other types of sensors used at Test Site 701.

The Comisión Nacional del Espacio Exterior (National Commission for Outer Space) of Mexico and the National Aeronautics and Space Administration of the U.S. are participants in an international program entitled "Plan for Cooperation Between Mexican and U.S. Agencies on Research of Remote Sensing for Earth Survey." This program has four phases: (A) cooperative study and research in the United States, (B) Mexican program development, (C) NASA aircraft flights over Mexican test sites, and (D) operational flights by Mexican aircraft. To date, this program has been completed to phase C.

In accordance with phase C commitments, a NASA NP–3A aircraft equipped with remote sensors flew over the El Oro-Tlalpujahua test site and five other sites in central Mexico in April 1969. NASA's mission was designated Mission 91, and El Oro-Tlalpujahua was designated Test Site 701. The only investigator was the author of this paper.

Test Site 701 was selected by the Council of Nonrenewable Resources, Ministry of National Heritage, to conduct economic geology investigations and compare several remote sensors. Other test objectives were to delineate better the already-known east-west and northwest-southeast trending fault systems; to complete, confirm, and refine geologic map unit contacts, taking advantage of rock and residual soil color variations; to seek new outcrops of two specific rock units, purple tectonic breccias and black shale, which indicate the presence of valuable mineral deposits; and to confirm the suspected existence of a northeast-southwest fault system.

SITE DESCRIPTION

Test Site 701 (figure 1) is approximately 130 km northwest of Mexico City. It lies between 19°43′ and 20° north latitude and between 100° and 100°18′ west longitude. It has a rectangular shape of 30 km north-south by 25 km east-west, with an area of 750 km². Its elevation above sea level varies between 3355 meters at the top of San Miguel Peak and 2135 meters at the Pateo railway station, and its climate ranges from temperate to cool, with an annual rainfall averaging about 90 cm.

This zone forms part of the Lerma River Basin, which drains into the Pacific Ocean, and its natural

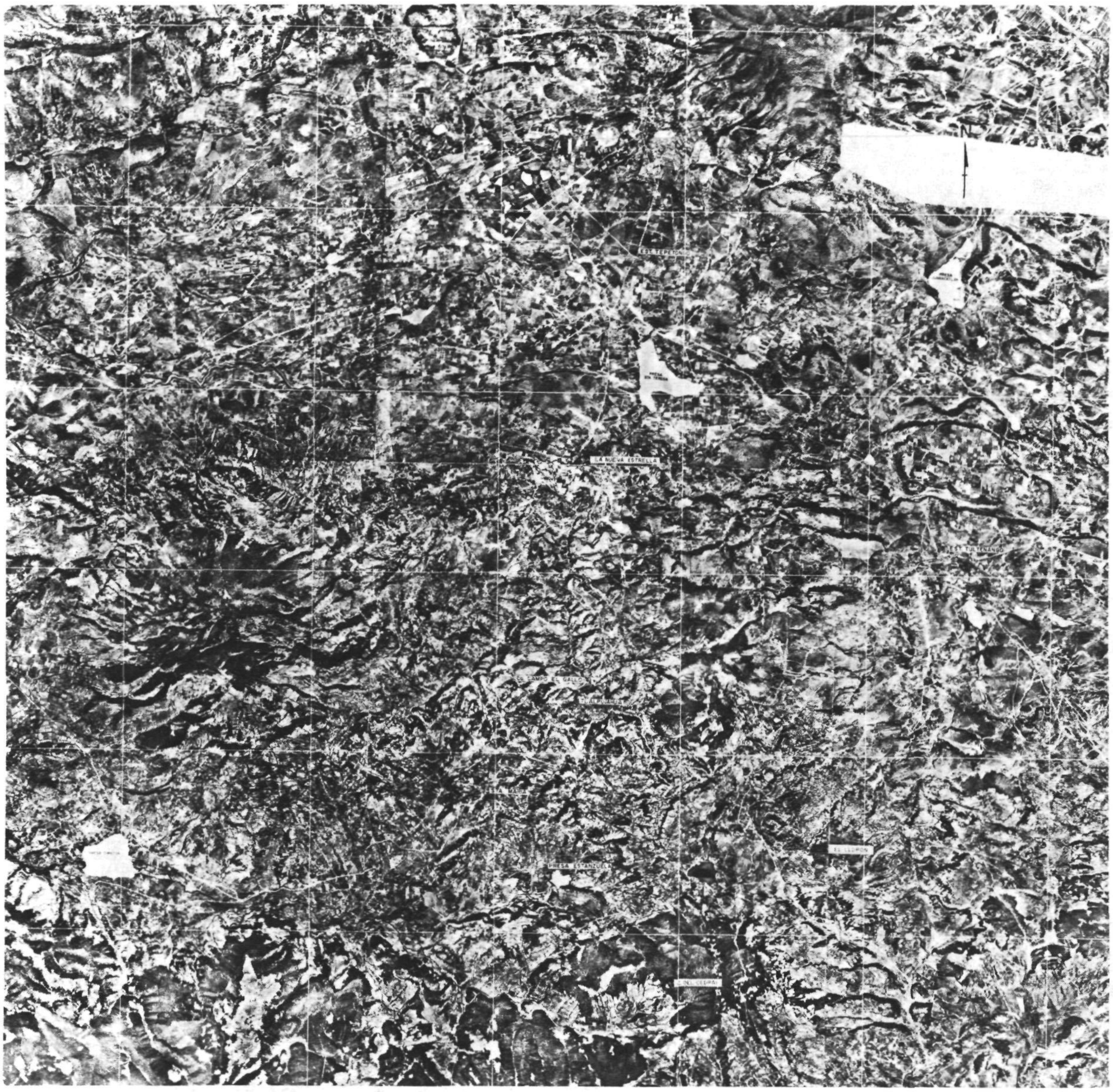

FIGURE 1. Noncontrolled rectified photomosaic of Test Site 701.

vegetation consists mainly of pine tree forests. Its main crops are corn, wheat, and fruit trees.

It has three old mining camps (El Oro, Dos Estrellas, and Tlalpujahua) which, near the turn of this century, were among the main producers of gold in Mexico. All of the mines are now inactive due to the exhaustion of known quartz-gold veins. The region has both economic and social problems due to dense population, insufficient jobs, erosion in scarce agricultural areas, and lack of technical exploitation of the forests.

GEOLOGY

The geology of Test Site 701 is rather complex. Starting in the usual sequence, from pre-Cretaceous to Holocene, the rock formations are folded and faulted schists, black shale, and limestones; small outcrops of dioritic instrusions; tilted and faulted purple tectonic breccias; several types of faulted andesitic flows; faulted andesitic and basaltic andesitic ignimbrites; some rhyolitic dikes; andesitic tuffs and breccias; faulted basaltic andesitic and basalt flows; lacustrine deposits; volcanic basaltic

tuffs; and alluvium. Premineralized northwest-southeast fissures were filled with gold- and silver-bearing quartz in black-shale host rock with intense folding and faulting due to Laramide orogenesis. Postmineralized east-west fault fissures and a northeast-southwest fault system are now known to exist.

Key rock formations for valuable mineral deposits comprise black shales (usually covered by andesitic flows) and purple tectonic breccias with angular and semiangular coarse stratified fragments of black shale, limestone, and quartz without fragments of volcanic or instrusive rock.

Geomorphology shows mainly reconstruction of the erosion cycle. The prior surface consisted of an elevated plain of metamorphic and sedimentary rocks covered recently by overflows of effusive material and pyroclastic deposits. All show the present physiographic aspect of peaks, hills, mesas, valleys, and ravines.

The east-west postmineralization fault fissures belong to the large neovolcanic fault system, and some isolated faults in the northeast-southwest trend seem to be the youngest. There is some doubt about the age of the northeast-southwest faults, but that does not preclude the likelihood that all of the faults have been active for several geologic periods in this region of block mountains.

REMOTE SENSOR DATA

In November 1968, before NASA's Mission 91, the Council of Nonrenewable Resources flew over the test site and obtained complete black-and-white stereo photographic coverage of the entire area at a scale of 1:15 000. Black-and-white infrared aerial photographs of the northern part of the site at a scale of 1:25 000 were taken in March 1969. In addition, some older black-and-white photographic material taken in 1960 and 1956 at scales of 1:25 000 and 1:45 000, respectively, is available. The black-and-white photographic material of the council was used in the elaboration of topographic maps at scales of 1:10 000 and 1:25 000, and in working out a photogeologic map at a scale of 1:25 000, because of a lack of adequate forward overlap in NASA's aerial photographic material. Nevertheless, all the materials gathered by remote sensors aboard the NASA aircraft have been extremely useful.

Sensor equipment on the NP–3A aircraft included two Wild RC–8 metric cameras with 23-cm format, one loaded with Ektachrome MS Aerographic film, type 2448, with a clear AV filter, and the other with Ektachrome IR Aerographic film, type SO117, with a Wratten 15 filter; one Texas Instruments dual-channel infrared RS–14 imager operating in the 3.0-to-5.5-μm and 8-to-14-μm ranges; and a Philco side-looking radar operating at a frequency of 16.5 GHz.

The NASA mission provided color and infrared color aerial Ektachrome film coverage of the entire test area with resulting material at a scale of 1:25 000; infrared scanner imagery from two channels at a scale of 1:60 000; and partial coverage with radar imagery, polarized H-H and H-V, at a scale of 1:350 000 (seven long east-west flightlines at 3800 meters above terrain, but radar operated only over flightlines 1 and 7). Partial coverage of the area was obtained with the same cameras and film types at a scale of 1:10 000, and the infrared scanner was operated several times before and after dawn with both channels at a scale of 1:40 000 (six short flightlines at 1500-meter altitude northwest-southeast).

Ground truth was accomplished 24 hours in advance, during the flights, and 24 hours after the flights by a complete micrometeorological station at Estanzuela Dam, where readings of each instrument were taken every 15 minutes. For temperatures of the terrain and water bodies, a semicontinuous recording was kept during the infrared scanner flights.

To mark the flightlines at night, Omni-Strobe Mark I lights were installed at the ends of low-altitude flightlines, and they proved very effective. At the patio of the primary school of the Francisco I. Madero village, four square color panels forming a Greek cross shape were displayed; each arm was a square of colored paper (yellow, blue, green, or red) 20 by 20 meters, with a center square of open ground. This color target was easily seen, even from 3800 meters, and proved to be a very flexible, economical, and effective marker.

DATA QUALITY

Metric photography with color and infrared color film provided fine resolution and good clarity of detail, and very excellent false-color rendition was obtained with Ektachrome infrared SO117 film. Unfortunately, forward overlap averaged 41 to 56

percent for low-altitude flights and 45 to 56 percent for high-altitude flights, instead of the requested 60 percent minimum, making some material inadequate for full stereoscopic use.

Infrared scanner imagery in the 8-to-14-μm band was good, but that in the 3-to-5.5-μm band was not so good.

Side-looking radar imagery was not bad, despite its small scale, lack of contrast, poor ground resolution, and heavy graininess.

DATA COMPARISON

Figure 2 compares four photographic emulsions (only the color and infrared color films were exposed simultaneously). The inherent ability of infrared color film to penetrate haze, identify different materials, and indirectly detect soil moisture was far superior to other emulsions for photogeology in this area.

Most geological features (such as drainage patterns, types of erosion, changes in slope, textures, fissures and faults, contacts, and broad lithology) were easily distinguished on the color, black-and-white, and infrared black-and-white films; but the latter did not detect contacts between yellowish-red intemperized black shale and purple tectonic breccias, for which the infrared color film also showed its superiority. False color film produced a brownish hue over small outcrop areas of the purple tectonic breccias against the lighter brownish tone of the more extensive outcrops of the intemperized black shale. It is not yet known whether this subtle change in color represents a difference in microvegetation developed specifically over the soils derived from two rock formations or whether it is the detection of a slightly different temperature response of those rocks at the red end of the visible electromagnetic spectrum. Nevertheless, of all the emulsions, only that of infrared color film showed the areal extent of purple breccias over yellow-red intemperized black shale.

It follows that, at this site and for studies of economic geology, false color film (first) and color film (second) are superior to the black-and-white and infrared black-and-white films, although the latter types are less expensive.

Thermal imagery in the 3-to-5.5-μm band showed only small vegetation fires over the terrain of small farms in the neighborhood of El Oro and Tlalpujahua. But imagery in the 8-to-14-μm range had good contrast, mainly in postdawn flights. It distinguished andesites, basalt flows, tuffs, and alluvium. With a microdensitometer and electronic computers, some rock contacts could be traced; in checking these, however, there is need for much ground truth information, which is costly and time-consuming. Figure 3 shows two thermographs (predawn and postdawn) in the 8-to-14-μm band, whose coverage includes the area shown in figure 2. The predawn imagery furnished more thermal data; but these data were discernible in the postdawn imagery, which also showed topographic details. In any case, the elaboration of a geologic map is more easily accomplished by the use of photographic data. The study of all the thermal infrared imagery is still in progress, however. As of now, it appears that infrared thermal imagery will be useful in economic geology in only a few specifically oriented investigations, such as searches for active faults, ore bodies associated with thermal activities, geothermal zones, and so on.

Figure 4 shows two strips of radar imagery from flightline 7, one with horizontal-horizontal and the other with horizontal-vertical polarization. Together they present a pseudostereoscopic view of the northern part of Test Site 701. Despite small scale, poor ground resolution, lack of contrast, heavy graininess, and some blurred strips, the radar imagery showed the three main fault systems, trending northwest-southeast, east-west, and northeast-southwest.

The almost vertical walls formed by columns of basalt flows in the Lerma River canyon functioned as a trihedral reflector for the radar, showing prominently in the imagery. Also radar shadows were noted from San Miguel El Alto Peak and some east-west faults over Tepetongo Valley, where there are some young volcanoes. (One of the volcanoes lies in the intersection of two faults, one running northeast-southwest and the other in a northwest-southeast trend).

Radar imagery thus furnished confirmation of the third fault system and proved useful in tectonic studies, which are important in investigations of economic geology.

SOME PRACTICAL RESULTS

Interpretation of our remote sensing imagery has resulted in:

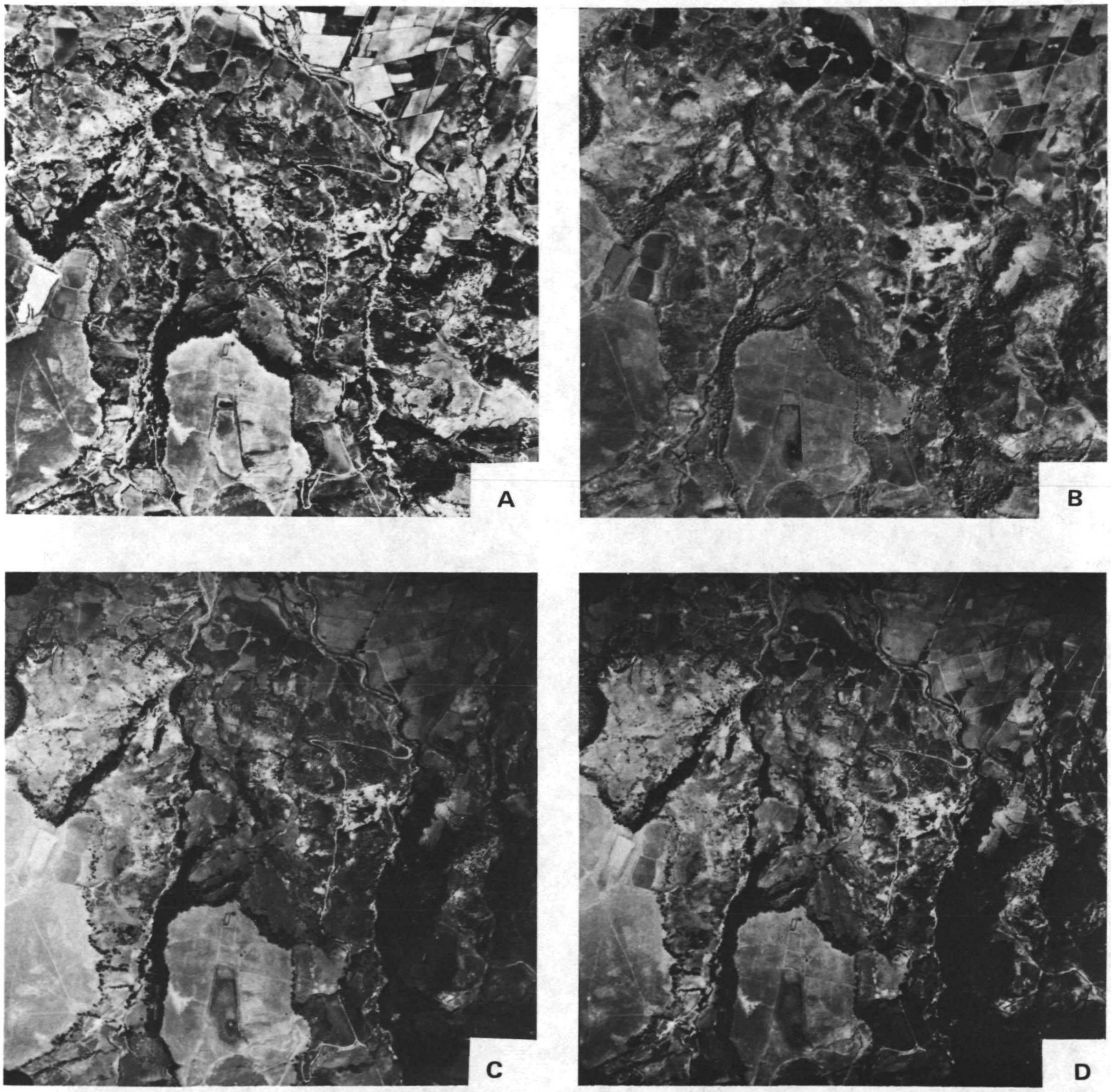

FIGURE 2. Comparison of four photographic emulsions (A, black-and-white panchromatic; B, black-and-white infrared; C, Ektachrome (color); D, color infrared).

(a) A photogeologic map of the entire area, based on black-and-white photographs with the help of false color and color photographs.

(b) Pseudostereoscopic H-H and H-V radar imagery that confirmed the presence of a third fault system running in the same direction as vein ore bodies of the Angangueo mining district, which remains active.

(c) Infrared color imagery that permitted the location of scattered outcrops of purple tectonic breccia. Its topographical situation (derived from fault movements), combined with rough stratification, allowed its origin to be located in a zone slightly southeast of Tlalpujahua, below El Cedral Peak, which is composed of andesitic flows and associated pyroclastics covering folded, faulted, and eroded black shale. Since black shale is the host rock of ore veins in this region, this knowledge may possibly lead to the discovery of important new mineral deposits.

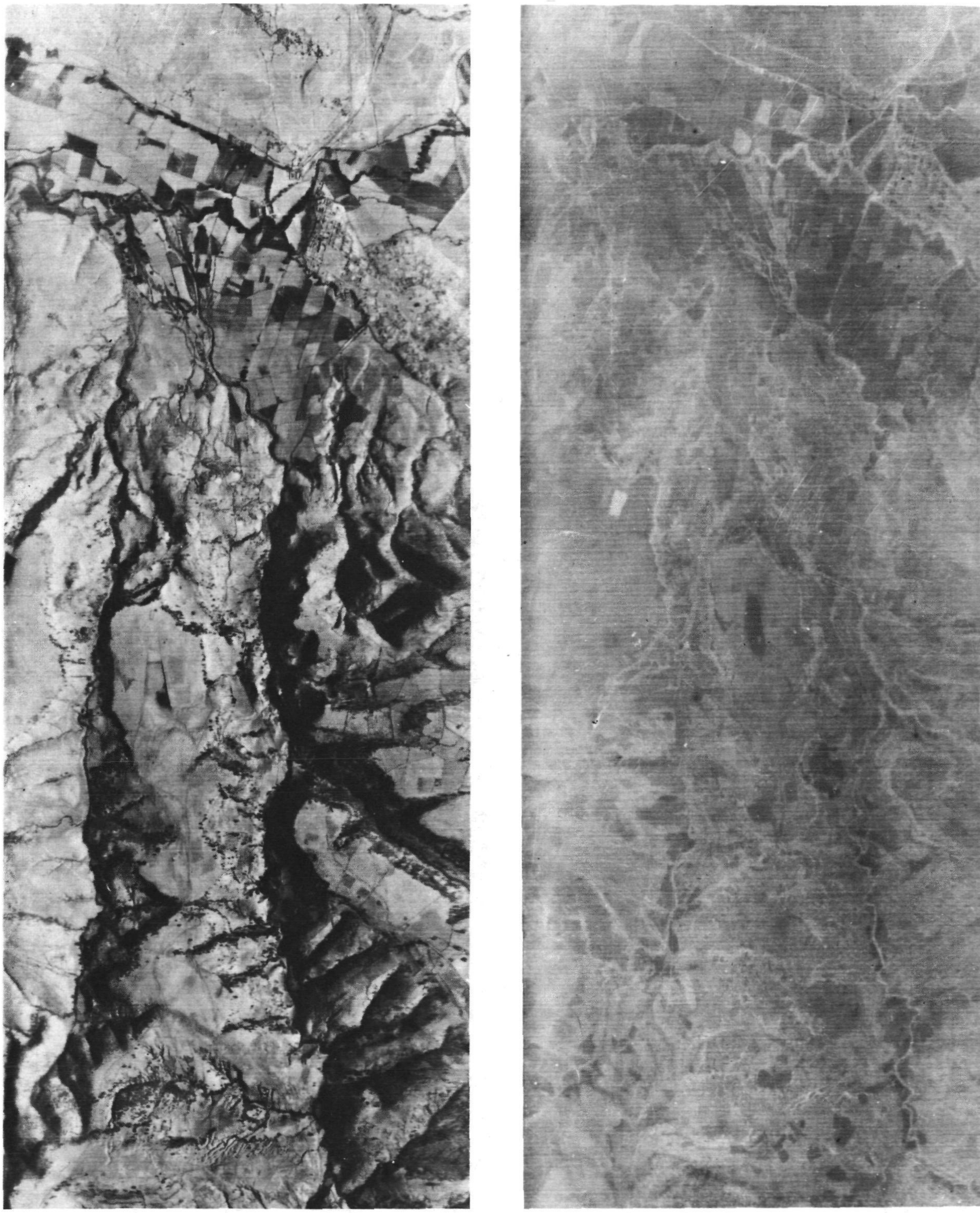

FIGURE 3. Thermographs recorded in 8-to-14-μm band before dawn (left) and after dawn.

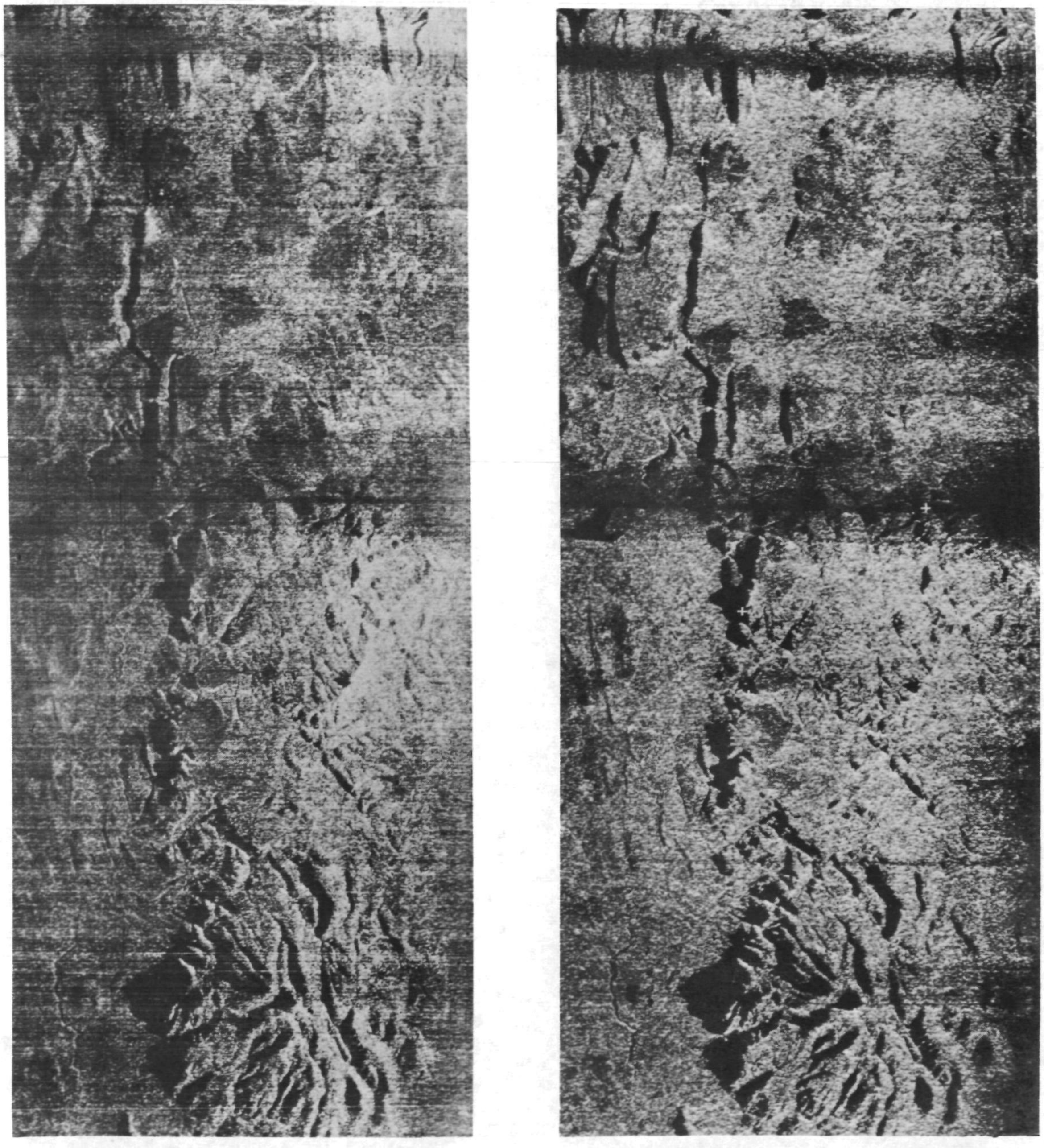

FIGURE 4. Radar imagery with (left) horizontal-horizontal and (right) horizontal-vertical polarization, forming pseudostereoscopic view of north-central part of test site.

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Remote Sensing Program at Test Site 701, El Oro-Tlalpujahua, Mexico

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The *Secretaría de Obras Públicas* (Ministry of Public Works) of the Republic of Mexico participated in the experimental stage (NASA Mission 91) of the Remote Sensing Program in April 1969. The main purpose of this participation was to compare information obtained from the new images with that provided by panchromatic and IR black-and-white aerial photographs hitherto employed by this ministry.

The images analyzed correspond to El Oro-Tlalpujahua, Test Site 701, located within a survey strip pertaining to a section of the new Mexico–Morelia highway (figures 1 through 4).

Comparisons were made from the standpoint of highway and railroad engineering—which is the main activity of this ministry—to evaluate the advantages of new techniques for photogrammetric electronic highway design. Table 1 describes the materials analyzed.

Each type of image was interpreted separately in conjunction with ground information obtained during the flight period, and the interpretations were subsequently checked in the field through 22 control points.

For our purposes, the relative advantages of remote sensors employed in this project were evaluated on a scale of 10 with the results shown in table 2. Figures 5 and 6 are aerial photographs showing geological data obtained from the color photographs.

Our results indicate that some of the new types of remote sensing imagery may indeed be helpful for highway design and location. In the immediate future, we plan to use color and IR color photographs; later on, IR and radar imagery.

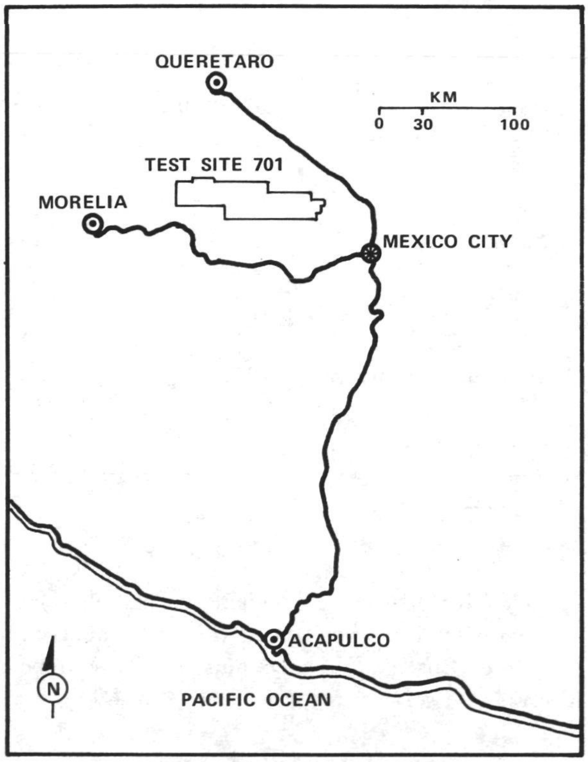

FIGURE 1. Location of SOP Test Site 701, El Oro-Tlalpujahua

Our ministry also plans to acquire two 70-mm Hasselblad cameras with 40-mm-focal-length lenses. These cameras will be operated together with the RC–8 camera aboard one of our aircraft, and we hope to put this system into operation within a year.

We are planning to employ IR imagery and side-looking airborne radar jointly with other federal

Table 1. Survey materials analyzed

Image type	Electromagnetic range (wavelength)	Working material	Scale	Flight date	Remarks
Panchromatic	450 to 700 nm	Positive prints on paper	1:25 000	18 July 69	OK (SOP)
IR black-and-white	700 to 900 nm	Positive prints on paper	1:25 000 1:5000	19 Mar 69	OK (SOP)
Color Ektachrome 2448 MS Aerographic	450 to 750 nm	Slide film	1:25 000 1:10 000	10 Apr 69	Lack of stereoscopic continuity in 1:10 000 photographs (NASA)
IR color Ektachrome 8443 IR Aerographic	550 to 900 nm	Slide film	1:10 000	10 Apr 69	Lack of stereoscopic continuity (NASA)
IR imagery	3 to 5.5 μm 8 to 14 μm	Positive prints on paper	1:41 000 1:87 000	10 to 12 Apr 69	OK (NASA)
Side-looking airborne radar	1.5 cm	Positive prints on paper	1:320 000	10 Apr 69	Too small scale; low resolution (NASA)

agencies for reasons of economy. This plan will become effective when the National Commission for Outer Space of Mexico puts a fully-equipped aircraft into service.

CONCLUSIONS AND RECOMMENDATIONS

For the design of highways and other land transportation systems, as well as for applied geology in civil engineering and detailed soil mapping, it was found that different soils and their boundaries could be identified much better with color and IR aerial photographs than with panchromatic photography. It is therefore recommended that color and color IR be used for detailed soil mapping to simplify and reduce the cost of field checks and soil exploratory programs.

Rock outcrops and their contact with soils, as well as different types of rocks, can be identified much better and with greater confidence by means of color aerial photographs. The use of color films is therefore recommended for detailed geologic mapping.

Color IR aerial photographs are particularly recommended for investigating zones of potential landslides and seepage problems.

Radar sensors are considered adequate to detect fracture systems and geological structural conditions in areas where it is difficult to take aerial photographs because of bad weather, as in the case of the usually excessive cloud cover over the southeastern area of Mexico.

Table 2. Evaluation of the relative fitness of the materials analyzed

(Numbers from 0 to 10 represent increasing order of suitability)

Objectives to interpret / Image type	Panchromatic	IR black-and-white	Color	IR color	IR imagery	Side-looking airborne radar
Land use, type of culture	8	9	10	9	7	0
Identification of land communications and all types of structures	9	9	10	10	7	5
Urban development	9	9	10	10	7	7
Culture types	7	10	9	10	7	0
Delimitation of geomorphical elements	10	10	10	10	7	7
Definition of rocks and soils	8	8	10	10	8	7
Determination of rock types: their fracture, weathering conditions, and metamorphism	9	8	10	9	8	8
Failure and fault location	9	9	10	10	9	8
Identification of different types of soils: their origins, stability, depth, plowability, granulometry, plasticity, moisture, and organic material content	8	9	10	10	8	7
Localization of unstable or potentially unstable areas due to weathering, seepage, tectonism, etc.	7	8	9	9	8	7
Basin definition and detailed identification of hydrographic characteristics	9	10	10	10	9	8
Identification of river beds, stability, runoff cycles, erosion, reservoirs, geological features of river beds and river banks, flood areas	8	8	9	9	8	6

NOTE: Figures 2, 3, 4, 5, and 6 are located at the back of the book.

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Remote Sensing in India

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This paper describes a small remote sensing project for the early detection of a wilt root disease affecting coconut palms in Kerala State, India, and outlines the construction of an infrared scanning camera by the Indian Space Research Organization in collaboration with the Laboratorie de Meteorologie Dynamique, CNES, France. Work being done by other Indian organizations in the field of remote sensing is also discussed.

REMOTE SENSING OF COCONUT WILT ROOT DISEASE

India has successfully conducted a small remote sensing project for the early detection of a virus disease. Known as the coconut wilt root disease, it is especially damaging to coconut palms in the Travancore-Cochin area of Kerala State in South India. It affects about 400 square kilometers of plantation and is estimated to reduce annual income in the area about 10 million rupees or $1.3 million. Hence, any method of detecting the disease early will be of great economic value when a cure is also found.

The disease apparently became significant after the floods of 1882. It is characterized by symptoms of wilt accompanied by the flaccidity of young leaves and abnormal leaf bending. Also, the outer whorl of leaves often shows premature yellowing.

The normal annual yield of a palm in Kerala is about 60 nuts, while elsewhere it is nearly 100 nuts. When a tree is severely diseased, its yield is practically nil.

Recent studies have shown that the disease is caused by a virus visible as rods under an electron microscope (ref. 1). This was suspected by Shanta and Menon (ref. 2), who discovered that the disease could be mechanically transmitted to cowpea (*vigna sinensis*) by rubbing the leaves together.

By the time the disease is normally detectable to a farmer, the tree roots have begun to rot. They are full of virus and so is the surrounding soil. All a farmer can do then is to cut the tree down, remove its roots and surrounding soil, and burn them to prevent the infection of other palms.

Following a request from the Indian Space Research Organization (ISRO), NASA sent a scientist to India in February and March 1970 to help photograph coconut plantations containing healthy and unhealthy palms from an aerial platform. He brought a 70-mm Hasselblad camera and various types of film, including the color Ektachrome infrared type.

A large number of plots including different soil groups, experimental station plots, and cultivators' plantations with both healthy and unhealthy trees were photographed with the Hasselblad camera in seven different combinations of wavelength bands. Exposures included color Ektachrome infrared film, Kodak 8443 film using an 89–B filter, color MS, ordinary 2448, and black-and-white panchromatic (+X) No. 2401 with red, blue, and green filters.

Density measurements along a diameter of the image of a palm's crown were made with a non-recording Hilger microphotometer. White light as well as red, blue, and green filters were used to identify sensitive signature regions. A large number of exposures were made of healthy and diseased

palms from altitudes of 150 and 300 meters in a helicopter flying at a speed of 100 km per hour.

Simultaneously, leaf and soil samples were collected from selected trees from both healthy and diseased plantations for analysis in the laboratories of the Indian Agricultural Research Institute, New Delhi, and the Central Coconut Research Institute, Kayamkulam, Kerala. The analyses were carried out at these stations to correlate ground truth observations with photographs, density measurements, etc.

Figure 3 is a picture of palms originally taken with Ektachrome camouflage false-color film. The trees' crowns and leaves appeared bright red, while the nearby jackfruit trees appeared to have an even brighter red hue. The latter trees are native to the tropics and yield large edible fruits with a pineapple flavor, weighing up to 45 kg each. Plants with dull red or pink hues were cashew nut trees. This picture illustrates the practical results that can be obtained from the use of infrared photography for making tree inventories.

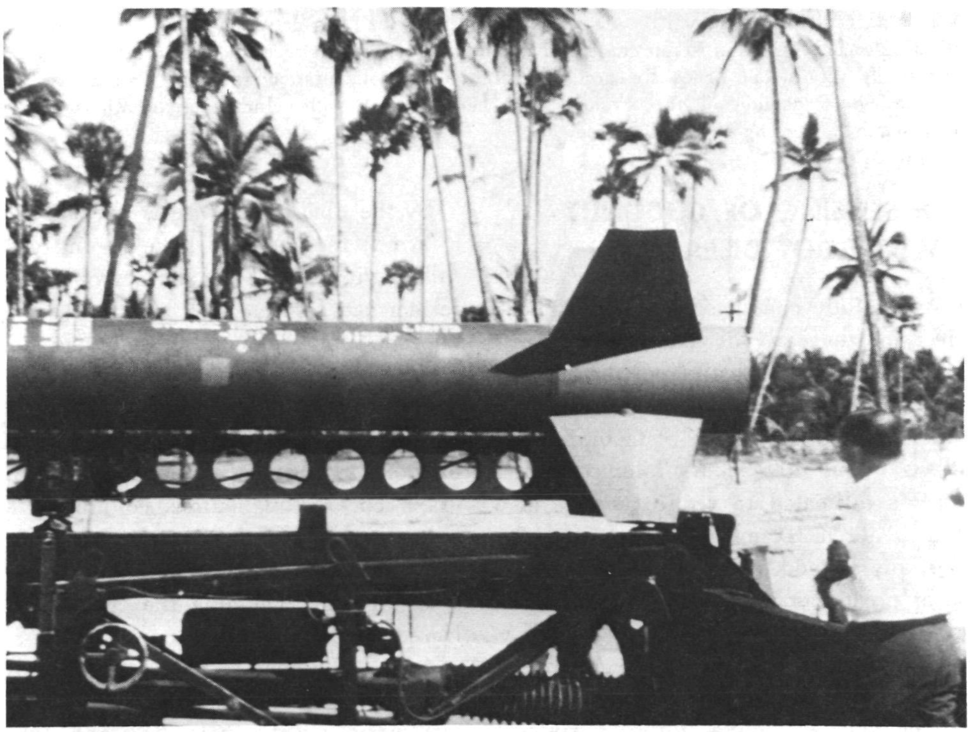

FIGURE 1. This photo of a rocket and launcher at a missile site in Kerala State shows a group of tall coconut palms in the background.

RESULTS AND DISCUSSION

Figure 1 shows coconut trees at the Thumba Equatorial Rocket Launching Station, an international rocket range in Kerala State. A rocket ready for launch appears in the foreground.

Figure 2 depicts a seriously affected tree that had to be cut down and destroyed, along with the roots and surrounding soil, to prevent further infection.

Figure 4 gives the optical density of coconut crowns appearing on false-color infrared film. They were scanned along a diameter of each crown. A healthy palm showed a significant decrease in the optical density at the center of it crown. The lowest curve in figure 4 pertains to a diseased palm. When its semipurified sap was subjected to an examination through an electron microscope, virus

FIGURE 2. A coconut tree severely infected with wilt root disease.

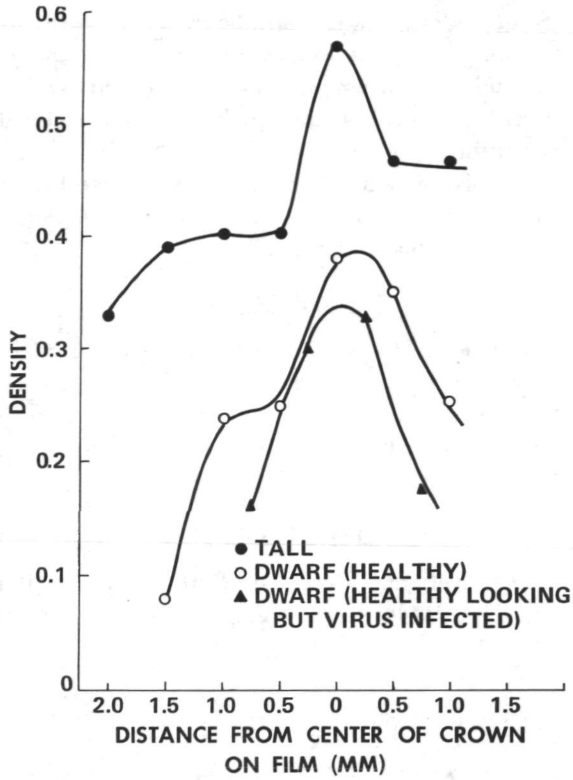

FIGURE 4. Plotted intensity measurements along a diameter of the crowns of three coconut trees.

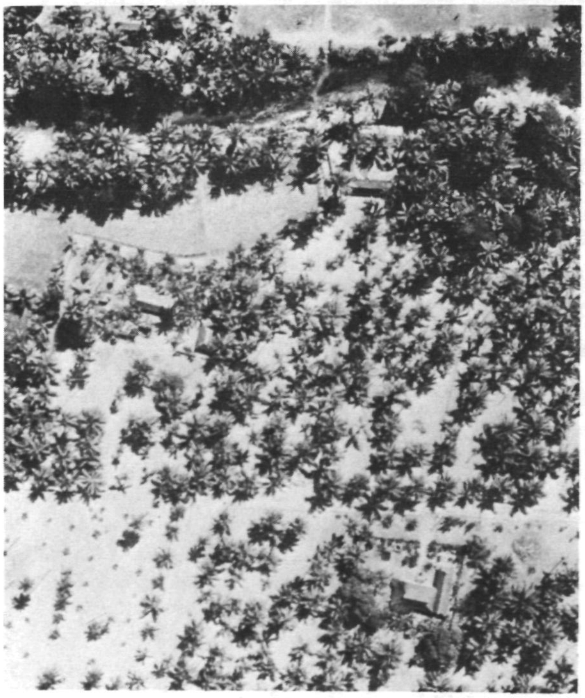

FIGURE 3. An aerial view of a grove area, taken with Ektachrome false-color film, that demonstrated the identification of various trees by spectral properties.

particles characteristic of wilt root disease were found. The sap of the other two trees whose optical densities are plotted in figure 4 did not have such virus particles. Of the illustrated varieties of palms, even the uninfected dwarf type had a lower optical density than the tall type.

A detailed paper on "Remote Sensing for Coconut Wilt" is being presented later this year (ref. 3).

I believe that remote sensing can be used to make inventories of teakwood and sandalwood trees, and possibly to detect stresses in such plants. Trees with long lives (50 or 60 years) can be expected to give radiation warnings of infections two to three years before they are seriously diseased.

INFRARED SCANNING CAMERA

A senior physicist and an electronic engineer are currently engaged in the construction of an infrared scanning camera for use in the 3-to-4-meter band from an aircraft platform. This camera is being constructed in one of the laboratories of CNES in

France. When ready, it will be used for the thermal mapping of oceans adjacent to India. It is expected that this instrument will reveal ocean surface temperature anomalies and gradients correlated with rich fishing grounds.

We also expect to use the new scanner for soil surveys and possibly to obtain data on forest animals such as the black elephant.

SNOW SURVEYS

The India Meteorological Department is studying variations of snow cover over the Himalayas, with the help of satellite cloud pictures, for experiments on the estimation of snow-melt contributions to Himalayan rivers.

OTHER STUDIES

The National Geophysical Research Institute (NGRI), Hyderabad, India, has been using airborne magnetometers and microwave transmitters, both of indigenous construction, for mineral surveys on an experimental basis.

The Geological Survey of India has been conducting aerial searches for minerals with airborne microwave transmitters as the result of short-term contracts with foreign commercial agencies.

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The Activities of the United Nations in the Area of Space Applications

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One could speak of the involvement and interest of the United Nations in the peaceful uses of outer space in terms of specific reports of the Committee on the Peaceful Uses of Outer Space and successive resolutions of the General Assembly over the years. While such a recital would constitute a fairly accurate reflection of events, it is nevertheless a rather dry account, hardly suitable to serve to an audience which has just enjoyed a very fine lunch. Instead, I would with your permission seek to give you my personal impression on this subject—an impression based upon less than a year of service to the United Nations as the expert on space applications.

It was clear to me in the early days of my appointment that the basic desire governing all UN bodies concerned was that the benefits from the exploration of outer space, in whatever form these benefits took shape, should be shared equally by all member States of the United Nations, irrespective of their economic or technological development. This basic philosophy has never been questioned. The only question has been how best the United Nations and the specialized agencies could fulfill this objective.

As a matter of fact, the specific mandate given to the expert on space applications by the Committee on the Peaceful Uses of Outer Space was to assess the resources of the United Nations family in the field of space applications and ascertain how best these resources can meet the needs of member States, in particular the less developed countries of the world.

Too often, as was emphasized yesterday, there is a tendency to generalize with respect to the needs of developing countries, as though all the countries faced the same problems, in the same time frame, with the same available resources. We know this is not true, even though in one sense a generalization is applicable. Many developing countries are not yet aware of the relevance of applications from space technology to the array of economic and social problems facing them in their task of development.

Even in countries where a small number of scientists are informed of space applications, this information is not readily transferred to those in government who make the policy decisions. There are many reasons for this situation, but it is sufficient to note that the United Nations has been consistently aware of the problem and has at every opportunity stressed the need for wide dissemination of information on the peaceful uses of outer space.

In pursuance of the latter objective, the United Nations in 1968 convened the first UN Conference on the Exploration and Peaceful Uses of Outer Space. Held in Vienna, Austria, the conference had as its primary objective the assessment of the practical benefits to be derived from space exploration and the means to share these benefits among all member States. It was in effect a worldwide exchange of information and ideas on the subject of space applications. The United Nations member States and the specialized agencies all contributed papers to this conference. I had the privilege of being in Vienna, and I was particularly impressed by the discussions that followed the formal presentations of papers. In these candid and informal discussion periods, one was constantly aware of the needs expressed by the delegations from developing

countries and the sincere desire to meet those needs expressed by the delegations from developed countries. As a strictly personal reflection, however, it was also clear that, unless a country had a clear concept of what it sought from space applications, the whole mechanism of cooperative assistance on an international, multinational, or bilateral basis would not operate productively.

If we examine the record, we see that cooperation in the implementation of space programs has been truly effective in only a few of the developing countries. In each case, the government of that country made a long range commitment of funds and personnel to a national program. To some observers the moral is clear: "God helps those who help themselves." In a certain way, it is reflected by this very workshop we now attend. The United States extended an invitation to attend this International Workshop to the entire membership of the United Nations, 127 countries, so that every member State had the opportunity to attend. Why then should we concern ourselves with those countries that, for whatever reason, did not attend?

Because we seek a better world not just for ourselves, but for all. Because we now understand that we are together on this planet Earth and our mutually interdependent relationship can determine whether we will have a better world to live in. And because we recognize that this new tool from outer space is indeed a global one with all the opportunities this affords. These are the reasons why we cannot merely sit back and allow the uninformed to remain so.

I do not, nor does the United Nations family, contend that applications from outer space will solve all problems. I do not, nor does the United Nations family, maintain that every country must become deeply involved in space applications. But we do say that every nation should be informed to the point where it can make a decision whether to get involved on the basis of its own best interests.

The thrust of a meaningful program for the United Nations in the area of space applications is not to duplicate the immense amount of technological data that has already been disseminated through many national and international meetings, but to translate the data to relate to the specific economic and social problems facing a country; not to persuade countries to pursue programs, but to determine whether techniques of space can more effectively and economically meet their needs; not to rush them into participation, but to detail step-by-step procedures for their participation if a space application program is to be meaningful to their scientific and technological growth and allow them to make decisions that are not overcommitting the future; not to consider only the offer of hardware, funds, and so on, but to advise where within the international community cooperative assistance might be sought and received; not to be the promoter promising salvation through space technology, but to be the prompter of the possibilities and potentialities. This, I say, is a role for the United Nations at this time and stage of the development of space applications.

It was in this spirit that the Committee on the Peaceful Uses of Outer Space, considering the role of meteorological satellites in the early years of the space age, encouraged the creation of the World Weather Watch and urged all member States to extend their national and regional meteorological efforts to implement this expanded program of the World Meteorological Organization. It was in this spirit that the General Assembly, after recognizing in its resolution 1721(XVI) that communications by means of satellites should be made available to the nations of the world as soon as possible on a global and nondiscriminating basis, invited the Special Fund and the Expanded Program of Technical Assistance, in consultation with the International Telecommunications Union, to give sympathetic consideration to requests from member States for technical and other assistance for the survey of their communication needs, so that they might make effective use of space communications. It was in this same spirit that the Outer Space Committee established a Working Group on Direct Broadcast Satellites to examine the technical feasibility of communications by direct broadcast satellites and to consider the economic, social, cultural, and legal implications of such a development. It was in this spirit that the General Assembly, in resolution 2600(XXIV), requested the Outer Space Committee to continue its studies with regard to the possibilities of further international cooperation, particularly in the framework of the United Nations system, in the development and use of remote sensing techniques to survey the Earth's re-

sources, so as to assure that the practical benefits of this new technology will be made available to both developed and developing countries.

It is in the same spirit that we are organizing the first of a number of panels to allow us to share the knowledge thus far gained—to give us the required information upon which to base decisions for our future action in this field—to exchange experience and information toward the common goal of advancement for the benefit of all.

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Canada's Approach to Remote Sensing

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Canada, like many other nations, is somewhat overwhelmed by the technological explosion in remote sensing. It combines aspects of the burgeoning technologies of space, sensors, and automatic data processing. Were it not for the fact that remote sensing bears promise of becoming an enormously powerful tool for gathering and sorting vast quantities of information on resources and the environment (two areas of vital concern to all governments), it would be dismissed as a luxury which Canada could not afford.

Rather than assuming a laissez-faire policy towards the development of remote sensing in Canada, attempts are being made at the federal and provincial levels to coordinate a rational development based on the following principles:

(1) Organizational planning should proceed on the assumption that remote sensing is not a transitory fashion, and it should therefore be established on an operational basis.

(2) The potential impact of remote sensing on methods of management of resources and the environment is of such importance that total systems planning, from sensor and sensor platform development through to the decision-making stages, should be undertaken.

(3) In such planning, every possible use should be made of available resources and organizational structures to achieve an orderly evolution.

(4) The high cost of the technology dictates intergovernmental, interdisciplinary, and interagency sharing of facilities whenever possible.

(5) The overall objective is to provide an economic and effective information system which can respond rapidly to the needs of resource and environment managers and policy makers.

Canada's progress towards accomplishing these ends is the subject of this paper.

The planned United States launching of the world's first resource satellite in March 1972 provides a keystone around which the Canadian program is organized.

Although well advanced in conventional aerial survey methods and photogrammetry, as well as in airborne geophysics, Canada has had little experience in remote sensing using multiband techniques and computer enhancement of data. During the last 5 years a limited amount of IR scanning and multispectral photography has been done. However, we do have a large territory to be covered and we have a large community of resource-oriented and environmental scientists and engineers ready to put the ERTS data to work when it is received.

For the past 18 months we have been involved in a fairly extensive planning operation, so that what is presented here is not what we have done in remote sensing, but what we plan to do.

ORGANIZATION FOR PLANNING

Canadians first became aware of developments in remote sensing in 1963 through the medium of the Symposia on Remote Sensing sponsored by the Willow Run Laboratories of the University of Michigan. At that time IR scanners were classified, and it was difficult to convince authorities of the usefulness of the method without Canadian examples. Proposals were put in to the government to set up remote sensing facilities in Canada, but they got

nowhere because of the expense of the technology involved, failure to prove a favourable cost/benefit ratio, and the lack of coordinated proposals by various agencies wanting similar equipment and facilities.

Later, when the EROS and ERTS programs were proposed, these helped considerably because, while it was conceivable that each concerned agency might run its own independent aircraft program, it was quite obvious that they each could not afford to run their own independent resource satellite programs, even if the satellite was being supplied by NASA.

This led to the setting up of an interdepartmental Committee on Resource Satellites and Remote Airborne Sensing.

To illustrate the widespread interest in this program in Canada, there are no fewer than 17 federal government agencies represented on this committee, which has been in existence since September 1969. The senior policy committee is supported by a full-time secretariat called the Program Planning Office.

The Program Planning Office proceeded to set up 13 *ad hoc* working groups in the areas indicated in figure 1, consisting of technically experienced advisers from government, university, and industry. There were from 10 to 15 members in each working group, so that all-in-all there were nearly 200 scientists and engineers involved. In addition to getting advice from these working groups about what to do about remote sensing in general and ERTS in particular, they served as an excellent education medium.

All these working groups have completed their work and are now publishing their reports.

In a couple of months, it is expected that this whole *ad hoc* organization will be replaced by a permanent Remote Sensing Centre and a Canadian Committee on Remote Sensing, which will have provincial as well as federal representation and which will also have a subcommittee structure similar to that shown in figure 1.

Since Canada has no space agency under which this program can be placed, it is necessary to set up what must seem like a rather elaborate committee structure to achieve adequate liaison. While the lead agency in this operation is the Department of Energy, Mines and Resources, a concerted effort is being made to give the organization an interdepartmental image—even to the extent of shared management and funding responsibilities.

Some funds were made available to the Program Planning Office last year for traveling expenses of all these working groups, for engineering studies, for a small aircraft program, and for phase A studies on a sensor development program.

Plans for a national program are now nearly complete, and of course they centre around the ERTS program as the keystone.

The elements of the proposed program are as follows:

(1) The establishment of a national facility in remote sensing, to be known as the Remote Sensing Centre. The lead agency will be the Department of Energy, Mines and Resources.

(2) The conversion of an existing 85-foot-diameter parabolic antenna at Prince Albert, Saskatchewan to serve as a dedicated satellite receiving station for ERTS data. This work is being managed by our Department of Communications, which has let the contract out to the University of Saskatchewan.

(3) A ground data handling centre capable of photogrammetrically correcting ERTS data as well as line-scan data from aircraft. This centre will be in Ottawa and will be located in the same building as:

(4) An enlarged Air Photo Production Unit (APPU) of the Surveys and Mapping Branch. This unit for 20 years has been responsible for the reproduction of all aerial photographs in Canada (with the exception of some handled by provincial organizations). It is expected that, as a result of the Remote Sensing Program, the throughput of the APPU will be nearly doubled.

(5) An expanded Air Photo Library. This library for 30 years has been the national repository for aerial photographs in Canada, and it has been possible for the public to get copies of any aerial photos taken in Canada for the cost of reproduction. It will now distribute remote sensing and ERTS data.

(6) An aircraft program. During last year and again this year, a limited aircraft program is being carried out. Multispectral photography, ultrawide-angle cameras, and IR scanners will be used. Areas have been selected by the working groups, and ground truth programs will be undertaken by users.

(7) A sensor development program in which industry and university laboratories are being funded

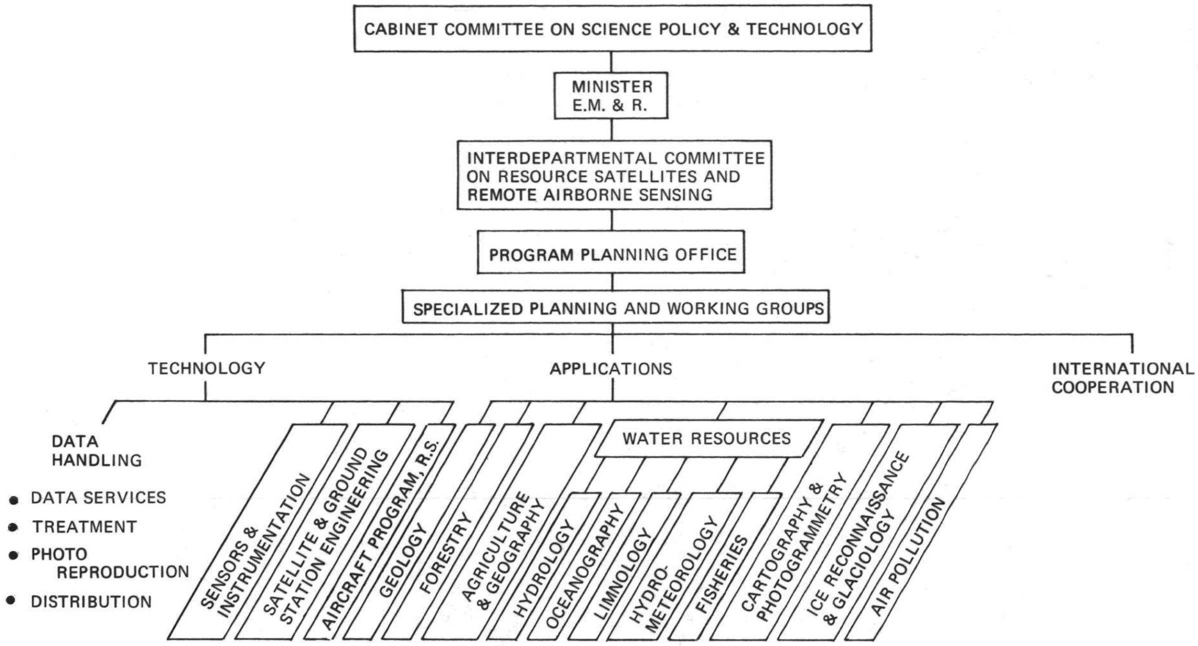

FIGURE 1. Interim planning organization for Canadian Committee on Resource Satellites and Remote Airborne Sensing.

to conceive and develop novel sensors to meet specific user needs. (This program was in operation last year and is being continued this year.)

(8) A research program into methods of enhancing remotely sensed data, as well as automatic methods of extracting information and displaying results. (This program has not yet been started.)

(9) The establishment of regional interpretation centres for analyzing available data within the area of their geographical jurisdiction is being considered by some provinces.

(10) The reinforcement of existing specialty centres for larger-scope interpretation of remote sensing data and ERTS data. For example, the interpretation laboratory of the Forest Management Institute will be enlarged. Two specialty centres in water resources will be established: one at the new Canadian Centre for Inland Waters for limnology and another in Ottawa for hydrology. The Canada Department of Agriculture will consolidate and enhance its interpretation capability.

(11) International cooperation in a longer-term look at requirements for future resource satellites and remote airborne sensing.

(12) The designation of ERTS test areas in Canada where interested agencies will undertake ground truth studies in conjunction with airborne and ERTS surveys.

(13) The establishment of a Canadian Committee on Remote Sensing, to be responsible through the Deputy Minister of Energy, Mines and Resources for governing the National Program on Remote Sensing and vetting the activities of the Remote Sensing Centre.

(14) An incipient program on data retransmission being collectively undertaken by several interested agencies.

PROPOSAL TO NASA

Canada has proposed to NASA 75 test areas in Canada where ground truth, and in many cases airborne work, will be done during or before ERTS orbit.

To take the load of receiving and handling all this data off NASA, Canada has also proposed adapting an existing ground receiving station in Central Canada (at Prince Albert, Saskatchewan) for ERTS reception. A data handling centre to be located in Ottawa is also proposed.

Figure 2 shows the range circle of the Prince

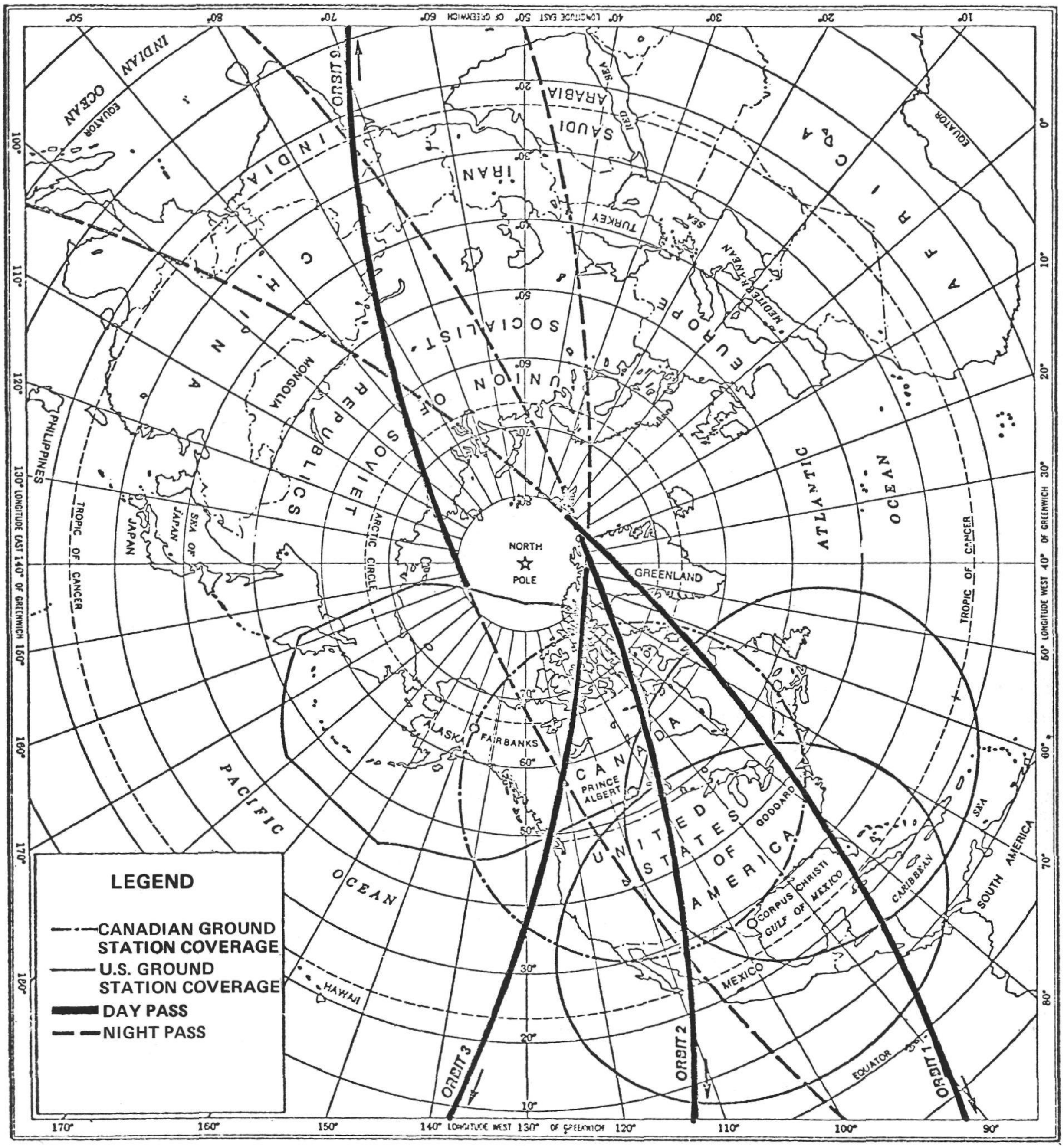

FIGURE 2. Map of Northern Hemisphere showing orbital passes of ERTS-A over North America and ranges of receiving stations in Canada and the U.S.

Albert station in relation to the proposed NASA stations at Goddard, Fairbanks, and Corpus Christi.

This Prince Albert station will have no command facilities, and it is intended to read out only Canadian data while the satellite is operating in the direct mode.

Tapes from Prince Albert will be air-expressed to Ottawa, where they will be photogrammetrically corrected by comparison with planimetry from 1:250 000-scale maps.

The same type of tape recorders will be used at Prince Albert as at Goddard so that tapes can be interchanged between those two stations.

Since Canada wishes to get as much data as possible of Canadian terrain, NASA has been requested to switch to the direct mode over Canada as much as possible. This would of course be subject to the power budget on the satellite, to the need to read out taped data at Fairbanks or Goddard during passes over Canada, and finally to calibration requirements of the MSS sensor.

Orbital parameters and "predicts" will be requested from NASA so that the Prince Albert station can acquire the satellite as it appears over the northern horizon. Autotracking will be employed once the signal is detected. Both the housekeeping and 2.2-GHz data will be recorded.

Although the DCP data from the six Canadian ground data platforms will be received, Canada will not have the capability of unscrambling, and NASA has been requested to do this.

The Communications Research Centre of the Department of Communications, which is managing the Prince Albert Radar Station, is planning a quick-look facility there using a high-resolution CRT.

A full study of what is required to be done to convert the Prince Albert station for ERTS use has been completed, and a contract will shortly be let to have the work carried out.

As far as a permanent resource satellite receiving station for Canada is concerned, Churchill, Manitoba would have been a better location as far as coverage is concerned, but for this experimental program it was decided to economize by using an existing station. The antenna at Prince Albert (figure 3) is a surplus dish which was used up until 5 years ago for research on radio propagation through the auroral zone. Since proposals have been made to move Earth resources satellite frequencies from 2.2 GHz to 8 and even 22 GHz to provide for more bandwidth, the Prince Albert dish will probably be rendered obsolete for the post-ERTS resource satellites.

CANADIAN COVERAGE BY ERTS

Figure 4 shows the total number of ERTS scenes per season in each latitude band across Canada. Notice how the number sharply increases as you proceed north, due to the converging orbits near the pole. As seen in figure 2, however, the satellite never passes within a circle 8° from the pole (82° N).

R. O. Chipman of the Program Planning Office conducted studies on cloud cover and Sun angle and came up with the probabilities for ERTS coverage with less than 10-percent cloud cover.

Figure 5 shows the number of pictures in each 10-scene cell expected in the summer season, taking into effect cloud cover and Sun angle. When the Sun angle is less than 10°, it is assumed that no imagery could be obtained.

There is concern that the combination of snow cover and a reasonably high Sun angle will saturate the sensor systems, allowing no usable imagery at these times.

THE GROUND DATA HANDLING SYSTEM

This is by far the biggest problem: how to convert the taped data into geometrically accurate imagery. It is also the most expensive.

There are essentially two types of tapes to deal with: (1) the pulse-code-modulated tapes from the multispectral line scanner and (2) the video tapes from the RBV. The data rates are extremely high, and there are four bands from the MSS and three from the RBV to deal with. Custom tape recorders developed by Ampex and RCA are required for the job, and they are both major pieces of equipment.

The simplest way to get imagery would be to display it on a CRT, as is done with the APT pictures, but this cannot be done without a great loss of resolution. Electron beam recorders or laser beam recorders, in which the beams play directly onto the film rather than onto the phosphor of a CRT, are used. This is relatively new technology and is having to be specially adapted for ERTS.

Before displaying the imagery either on a CRT

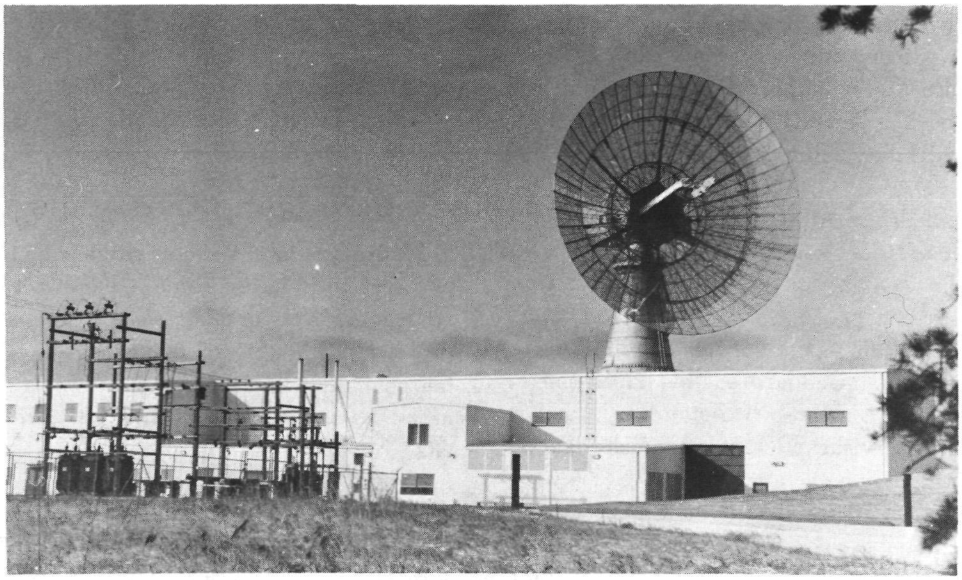

FIGURE 3. Prince Albert receiving station.

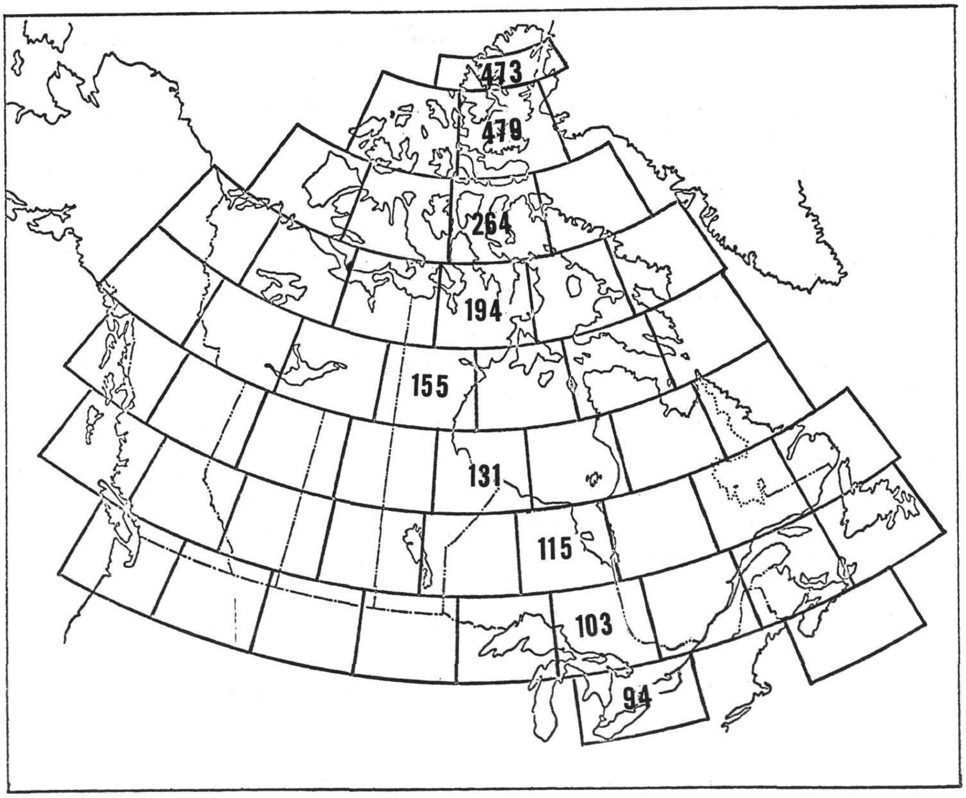

FIGURE 4. Total number of pictures to be taken over Canada in 1 year is 7934. The numbers on the map indicate the total pictures in each 342 000-km^2 area (all areas in the same latitude band have the same number). Illumination criterion for picture-taking is solar elevation $\gtrsim 10°$.

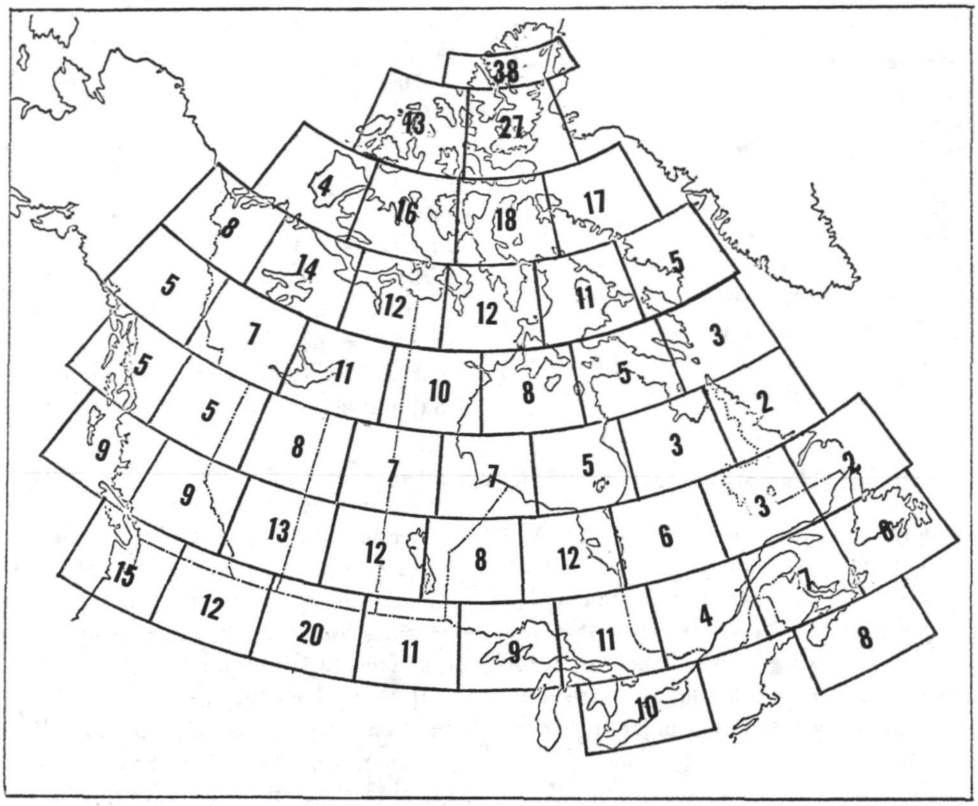

FIGURE 5. Total number of cloud-free pictures expected during summer season is 473. Map shows number expected in each area during conditions of cloud cover $\leq 10\%$ and solar elevation $\geq 10°$.

or on film, it is necessary in the case of the scanner data to demultiplex it and transform it to analog form from the pulse-code-modulated form. When it is printed out, it will be in a distorted form. Corrections have to be made to make the imagery conform to proper map coordinates. This is where the complication and expense arise. There is not space here to discuss the Canadian ground data handling system. Suffice it to say that it is very similar to the NASA system with a few exceptions:

(1) It will use an LBIR as its basic recorder rather than an EBR. This LBIR is capable of burning colour directly onto a colour film or alternatively it can burn black and white from one spectral band onto a pan film.

(2) The LBIR will have a double film transport which will allow for overlap on the 185-by-185-kilometer scenes and will also provide for annotation.

(3) While the MSS data should be as accurate as NASA's precision data, the same will not be true for the RBV data. Our RBV data will be corrected for obliquity and scale distortion and some of the pincushion distortion. We therefore do not expect to be able to make colour composites of the RBV data.

(4) The GDHC will be designed to handle airborne data as well as ERTS.

Air Photo Production Unit

Rather than setting up separate facilities for photographic processing, it is planned to use the facilities of the Air Photo Production Unit of our Surveys and Mapping Branch. For 20 years they have been responsible for reproducing aerial photos of Canada to meet customer needs.

With ERTS it is expected that their throughput will double.

It is planned to move this unit into the same building as the Ground Data Handling Centre, since the two obviously must work very closely together. New automatic processors, step and repeat printers, and composite printers are on order. This unit will

handle all the airborne remote sensing data as well as the ERTS data and of course the normal airphoto requirements. It will build up to a total staff of about 60 in the next 2 years.

The National Air Photo Library

Closely associated with the APPU is the National Air Photo Library, also operated by the Surveys and Mapping Branch. This library will essentially be the marketing agent for airborne remote sensing data and for ERTS data as well as for the normal air photography. Copies of all these data will be made available to the public at the cost of reproduction.

The Aircraft Program

On this program last year there was one CF–100 aircraft operated by the Canadian Forces. The CF–100 has a 181-kg payload, carries the pilot and a camera operator/navigator, has a range of 1850 km and an operating ceiling of 14 km. The Air Force supplies aircraft maintenance, flying, airframe engineers, avionics technicians, mission planning, hangerage, etc.

This year there will be one CF–100, one DC–3, and a small single-engine aircraft for detailed work.

Next year it is hoped to expand to three CF–100's, two DC–3's, and two small aircraft.

The main sensors are ultrawide-angle 23-cm square cameras, 70-mm multispectral pods, and IR line scanners. Multispectral line scanners will be acquired.

A Sensor Development Program

On the basis of parameter studies carried out by the seven user groups, requests for proposals were put out to industry and university laboratories for novel sensing devices to measure any of these parameters from aircraft or spacecraft. Fifty-four proposals were received, and 11 were funded for phase A studies. Nine of these 11 are being re-funded this year for phase B.

Again, there is not space here to describe them, but there is a publication coming out which will do so. Many of them use laser technology, some imaging tubes, some microwave. Air pollution, water pollution, sea-ice thickness, and water vapor content are some of the applications.

The Establishment of Regional Interpretation Centres

There are two main reasons for promoting the establishment of regional interpretation centres:

(1) In Canada the administration of resources and responsibility for the control of the environment comes under the jurisdiction of the provinces. End users and decision makers are mainly located within provincial administrations. By establishing regional centres of expertise in interpretation, it should be possible to get closer to the decision makers. Experience in photointerpretation shows that interpreters who have local knowledge of an area make the best interpreters.

(2) While it is expected that initially the bottleneck will move down from data acquisition to data correction and data reproduction, ultimately it will be in interpretation. Decentralization should alleviate this anticipated bottleneck. Such decentralization provides for greater grass-roots participation, which is obviously important.

It is expected that these regional centres will be autonomously operated by the provinces or groups of provinces. The provinces are just beginning to get organized on an interdisciplinary basis for the purpose of examining their needs.

Specialty Interpretation Centres

Several of the discipline-oriented federal departments already have airphoto and remote sensing interpretation facilities specifically oriented toward their own missions. For example, the Forest Management Institute of the Department of Fisheries and Forestry has for many years been active in airphoto and remote sensing analysis. They are presently expanding and equipping themselves to handle ERTS and new RS data.

The Inland Waters Branch of the Department of Fisheries and Forestry is planning specialty centres for remote sensing: one in limnology, to be located at the Canada Centre for Inland Waters, Burlington, Ontario; and the other in hydrology to be located in Ottawa.

The Burlington group and the Meteorological Branch located in Toronto are the two main Canadian participants in the International Field Year for the Great Lakes, which also begins in 1972.

International Cooperation in Remote Sensing

Up to the present, Canada has participated very little internationally, at least at the official level, in remote sensing activities, for the simple reason that no viable domestic program has existed. As capabilities and ideas are developed, fuller international participation is expected.

In the abstract it is stated that plans are being made under the assumption that remote sensing is here to stay. It follows that if Canada is going to the expense of putting up a data handling centre and a readout station, she is interested in what follows after ERTS. If for one reason or another the successor to ERTS is not suited to Canadian needs nor to the needs of some other countries, I would guess that we would be in the market for international cooperation in a resource satellite that does meet our needs. Alternatively, if the successor to ERTS looks good for Canada except for some minor modifications, I would also guess that we might like to buy into it in order to influence the design. I should hasten to add that this is only my personal opinion and not official policy.

ERTS Test Areas

In response to NASA's request for test areas, 75 test areas were proposed in Canada, as shown in figures 6 through 10.

In most cases these areas were not put up primarily because of ERTS. They are areas where various agencies are planning to do their normal work during the period of ERTS. ERTS data will simply be auxiliary or complementary to the ground and airborne data they already have and will be getting.

Using these people has several advantages over transitory short-term investigations: Experienced professionals in their fields of endeavour are employed. They will be able to place the remote sensing data in its proper context, and they already have contact with the decision makers in their areas. The disadvantage is that some of them may be inclined to be conservative in their approach to these data, but this can and must be overcome.

Canadian Committee on Remote Sensing

In order to coordinate this expensive national activity, to avoid duplication, and to share in re-

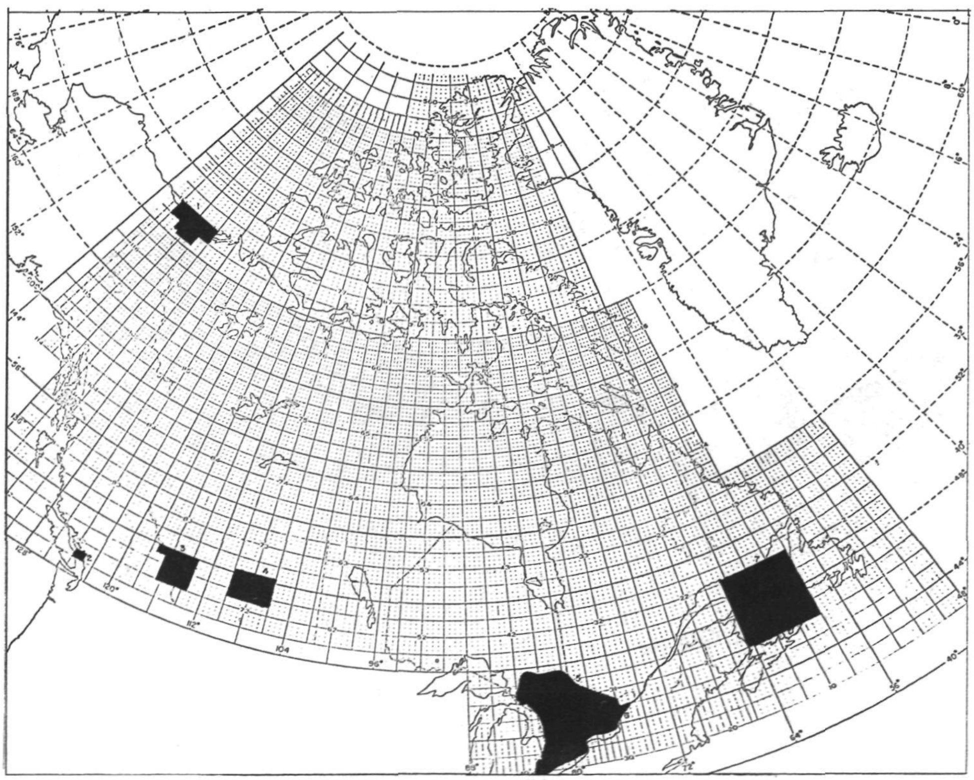

FIGURE 6. Water resource test areas.

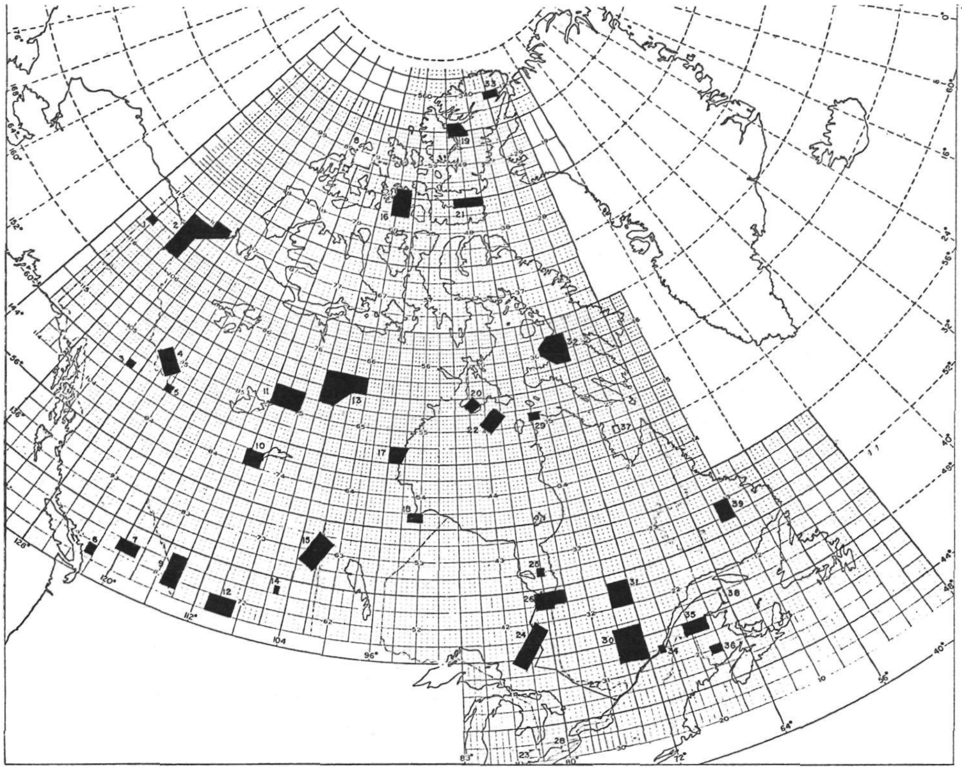

FIGURE 7. Forestry test areas.

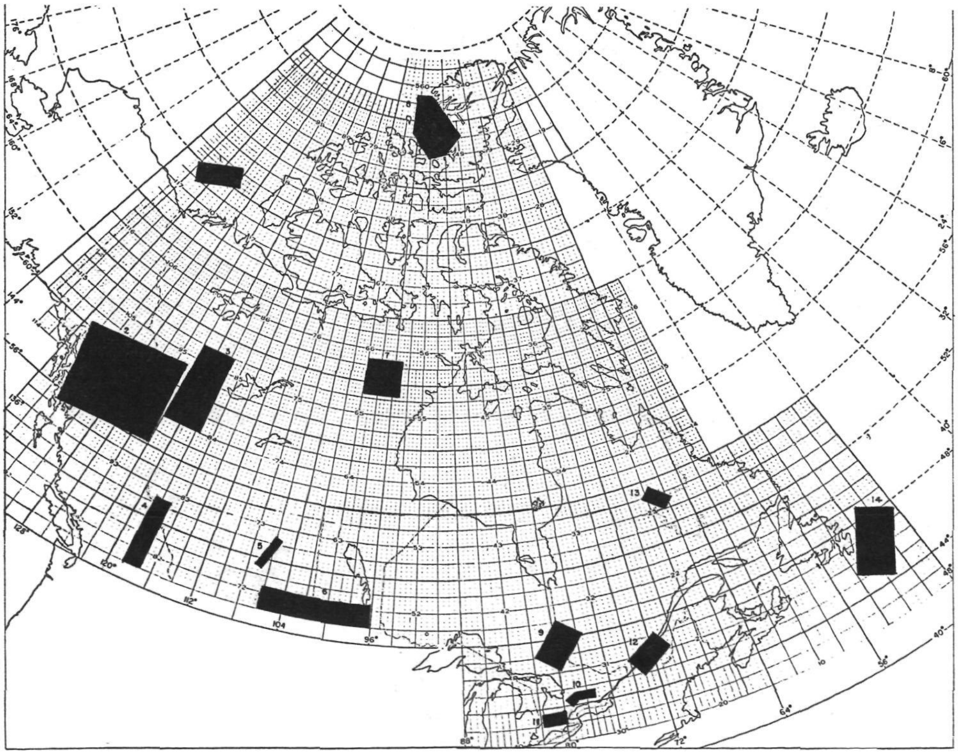

FIGURE 8. Geology test areas.

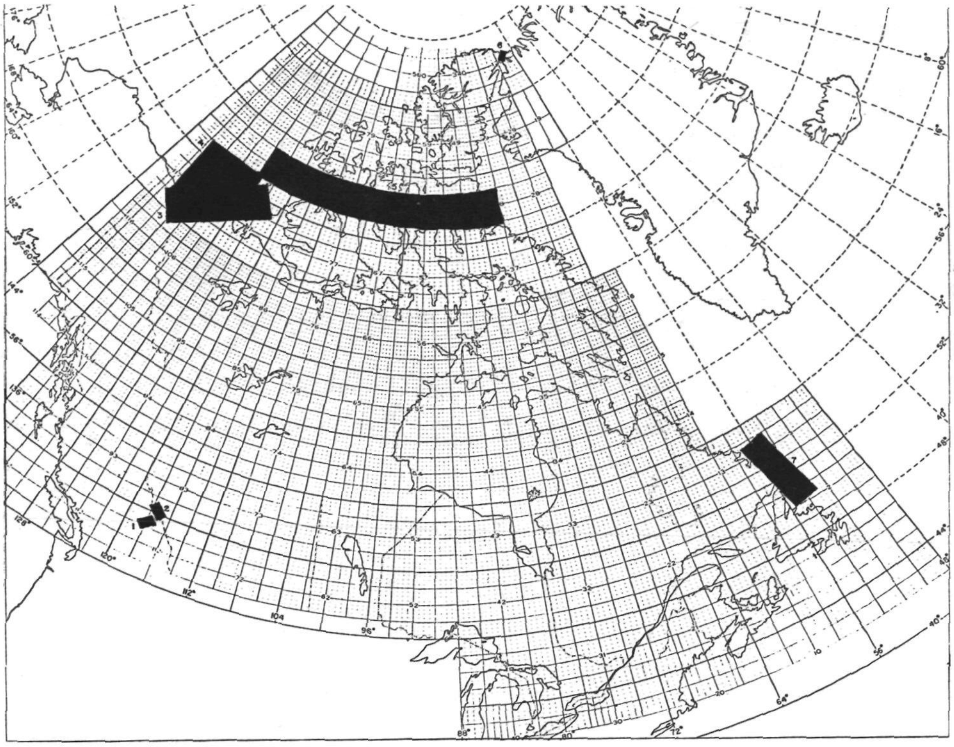

FIGURE 9. Ice reconnaissance and glaciology test areas.

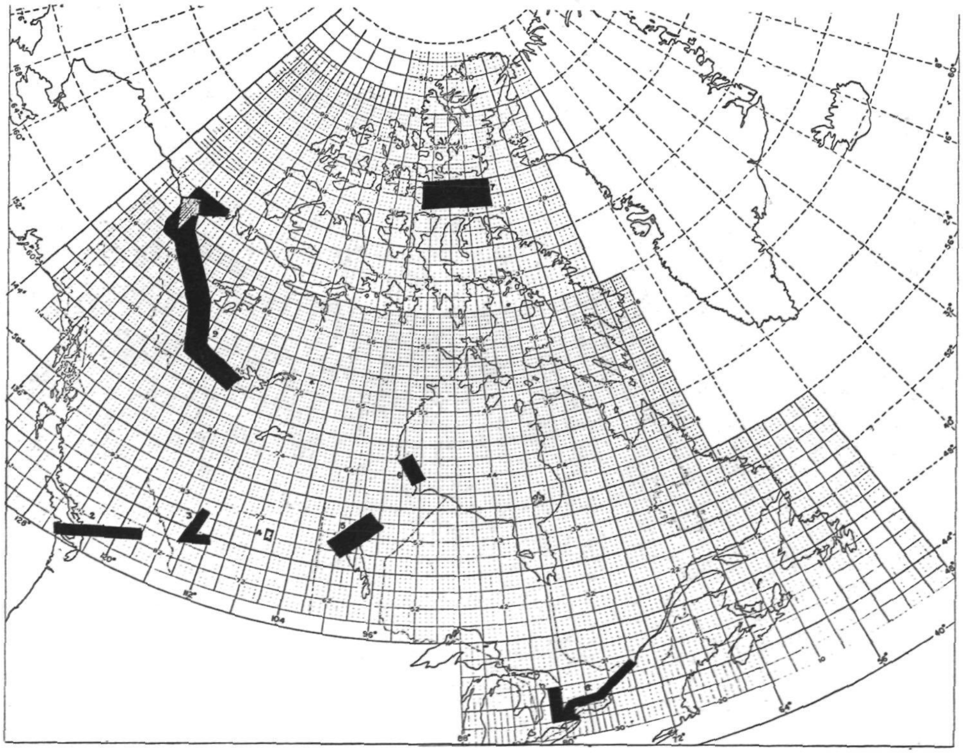

FIGURE 10. Agriculture and geography test areas.

search costs, it is planned to establish a Canadian Committee on Remote Sensing, which will govern the activities of the Remote Sensing Centre or National Facility. The membership of this committee will be comprised of representatives of provincial and federal organizations, as well as universities and industry. It will be organized somewhat along the lines of the various working groups of the PPO (figure 1), with a subcommittee structure to ensure wide representation.

CONCLUSION

While Earth-oriented observations are of considerable scientific interest, the main motivation behind the Canadian program in the next few years is the prospect of developing an operational information system for resources management and environmental control.

Thus the Canadian program, rather than being considered as part of a space science program, should more appropriately be considered as strictly an applied R&D effort in resource and environmental management. A concerted attempt will be made to achieve a proper balance among airborne, spaceborne, and surface data collection on the one hand and between hardware development and interpretation on the other hand.

The French Teledetection Program

AIME ALOUGES

French National Commission for Space Research

Since 1962, France has financed a government agency (CNES) to promote the development of space technology and to expand the national space policy. This agency, which has a budget of more than $100 million and employs a thousand people, has been able to build ground facilities and develop launchers and put seven satellites into orbit.

For several years, CNES has also been developing and coordinating a program for remote sensing with the aid of experts from different national agencies interested in the study of the Earth's surface, including:

- Bureau of Geological and Mining Research
- National Center for the Exploitation of the Oceans
- National Center for Scientific Research
- The Commission for the Mapping of Territory
- The French Petroleum Institute
- The National Institute of Agronomic Research

In addition, a French organization called the National Geographical Institute has assumed the task of preparing and updating topographic charts. To do this, it has a group of specially equipped aircraft for taking high-quality aerial photographs and facilities for photogrammetric restoration.

Since the National Center for Space Studies is concerned with studying the potential of a program of satellite observation of the Earth, it is natural that our primary interest should be directed toward the existing photointerpretations of various organizations interested in the Earth's surface.

We quickly found that the situation was far from ideal. First of all, the available photographs often date back several years, whereas the time factor is critical in certain studies whose success depends on immediate availability of results. Secondly, the photographs were generally taken on panchromatic film, which cannot *a priori* convey all necessary information in many cases. Thirdly, it was not generally possible to obtain repeated coverage of a given region. Finally, the idea of using other types of collecting devices, other methods of exploitation, and vehicles other than aircraft had not been adequately investigated.

For these reasons we decided it was necessary to have a first-phase exchange of reciprocal information between users and CNES, supported by preliminary experience, to determine the existing material that could be used in France.

The vehicle used for the resultant experiments was an aircraft owned by the National Geographic Institute, which we equipped with a battery of Hasselblad cameras (loaded with panchromatic, infrared black-and-white, natural color, and false-color film) and a French Cyclope infrared scanner operating in the 3-to-5-μm band. In addition, we had an infrared scanner operating in the 10-μm band adapted for computer analysis of results.

The definition of our airborne experiments was accomplished jointly by the group of users which we formed. The items defined included flight parameters, test sites, epochs and hours of flight, and scales of photographs.

Consequent flight operations involved two large test sites, one of which included the following portions of the Paris basin:

- Bay of the Seine for oceanography.

- Low valley of the Seine for studies of water pollution due to overindustrialization.
- Bray area for its geological characteristics; it is essentially an eroded anticline which reveals the different sedimentary layers of the Paris basin.
- School of Agriculture for applications to agriculture; the history of parcels there has been well known for more than 20 years, thus providing excellent ground truth data.
- Forest of Rambouillet for silviculture.
- Beauce, Valley of the Loire, and Sologne for pedology, hydrology, and vegetal ecology.
- Minervois, which offers in a small area (about 10 000 hectares) very great variations in altitude (150 to 1000 meters) and climate (rainfall varying from 50 to 120 cm), with a shift from Mediterranean to Atlantic conditions; also primary, secondary, and tertiary terrain that extends to the recent quaternary with highly different limestone and nonlimestone lithology and vegetation (both natural and cultivated) that reflects 2000 years of human habitation.

Such conditions allowed us to study:

- An integrated ecological approach.
- Productivity of vineyards.
- Cartography of vegetable fuels and land use.
- Geology, hydrogeology, and mining possibilities.
- Geomorphology.
- Archeology.

Our second test site, on the Mediterranean coast in the region of Montpellier, is a littoral belt including ponds that communicate more or less directly with the sea. This area offered the possibility of studies concerning mass water dynamics, sedimentology, biology of ponds, pollution, and culture of shellfish (oysters, mussels, etc.).

A third (southeastern) test site was added after our second flight to experiment with a remote detection technique for an advanced attack on trees by a scale insect (*Matsucoccus*) and to prepare for operational extension of the method to the forest of Landes, which (with an area of 1 million hectares) is one of the largest forests in Europe.

We conducted experiments in summer, winter, and spring to examine seasonal variations and determine relationships of variables (as in vegetation, soil, subsoil, and effects of man). Each seasonal experiment consisted of three flights: one in the daytime, one at nightfall, and one at sunrise. The first two experiments took place in July 1970 and February 1971. The third is planned for June 1971.

Initial results were encouraging. Since our main objective has been to prepare users for work with pictures from satellites, one feature of our work has been fine-scale photography.

For example, we placed a housing containing two cameras loaded with panchromatic and false-color film and a four-channel photometer beneath a stratospheric balloon which was allowed to attain an altitude of 32 km, producing pictures at a scale of 1:400 000. The surface area covered by each picture was 25 by 25 km.

As a vehicle for carrying out remote studies of the Earth, the stratospheric balloon had the advantage of being inexpensive and the disadvantage of having its course imposed by the wind at flight altitude. However, this disadvantage was handled with relative ease because the winds were rather stable and so well known that the balloon's course could be predicted with reasonable accuracy.

FUTURE PLANS

We are prepared to interrupt our airborne experiments in June to allow users to complete their interpretations of the data acquired and publish their findings. This suspension of operations will also enable us to make improvements of a technical nature and to equip an aircraft for automatic data analysis tests to be conducted in 1972.

We also have plans for future flights of stratospheric balloons.

We have made several suggestions to NASA for using the data from the ERTS-A satellite. They came from various French multidisciplinary organizations, and some involve test sites we have already surveyed.

SESSION VI

Chairman: A. G. Norman

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Introduction to Sensors

Gwynn H. Suits

Research Physicist, School of Natural Resources,
Institute of Science and Technology,
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A remote sensing system utilizes a sensor to make radiometric measurements so that an interpreter can infer what substances or conditions of interest exist at remotely located positions. Important sensor types are the (1) photographic camera, (2) video camera, (3) optical-mechanical scanner, and (4) microwave radar. Radiation properties which these sensors measure are summarized, and their respective methods of operation are illustrated.

A remote sensing system consists of a platform, a navigation device, an operator, a sensor or sensors, a data processor, and an interpreter (figure 1). The platform is an aircraft or spacecraft which carries the sensor, supplies power for its operation, and provides operational mobility. The navigation device (or method) determines the location of the platform and the area to be searched, while the operator (which may be either a human or an automatic control subsystem) causes the platform and sensor to perform in accordance with a search plan. The sensor makes radiometric measurements at each predetermined location and records the resultant data, so that it can be combined by the data processor with ancillary data to make it more interpretable. Then the interpreter uses the processed data to report the discovery, location, and/or quantity of items for which the search was made.

All parts of the remote sensing system are not always on the platform. Sensor data, for example, may be telemetered to the ground before data processing and interpretation functions are performed. Needless to say, the value of such data depends just as heavily upon its interpretation as it does upon its accuracy.

A sensor with a capacity to generate radiation is said to be active, and its radiation may be controlled in four ways, namely the ways in which it is (1) directed, (2) distributed in the spectrum, (3) polarized, and (4) allowed to vary in time or phase. Radiation returning to the sensor from remote objects can be measured to determine the direction from which it returns, its spectral distribution, its polarization, and the time variation or phase of its return. Generated radiation interacts with, and is altered by, remote objects in accordance with known natural laws. Therefore, the alterations of received radiation can be measured by the sensor. Successful interpretation then depends on the

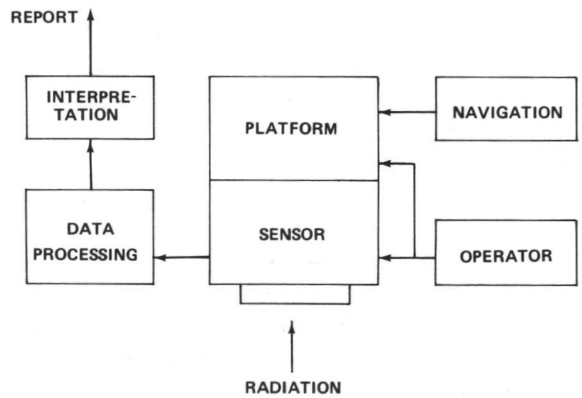

Figure 1. Block diagram of typical remote sensing system.

ability to infer the existence and properties of remote objects from measured alterations.

A sensor without a capacity to generate radiation is said to be passive, and it receives radiation generated by natural sources. The direction, spectral distribution, polarization, and emission time of the radiation cannot be controlled, and the sensor operator must wait for suitable radiation conditions to occur. The passive sensor can also measure the aforementioned qualities of radiation, as illustrated in figure 2, but the properties of the radiation will not normally be the same as that of radiation received by an active sensor. For example, measurements made by a passive sensor will not reveal alterations effected by remote objects, because all initial properties of the radiation will not be known.

Since most natural radiation is thermally generated in accordance with well known natural laws, it it is often sufficient to infer the properties of the radiation from a few measurements made by the sensor.

Passive sensors are frequently less expensive than active sensors because passive sensors do not employ a radiation generator. However, the fact that an operator may have to wait for suitable naturally generated radiation conditions could increase the cost of operating the remote sensing system and adversely affect the timeliness of a final report.

Perhaps the oldest remote sensor, other than the eye, is the camera (figure 3) using black-and-white photographic film. Daylight radiation is used, with the Sun angle selected in accordance with the time of operation. Spectral distribution is not measured with this sensor, except to establish that there is sufficient solar irradiance in the visible wavelengths (400 to 700 nm) to expose the photographic film. The direction of received radiation is recorded with good accuracy within a large field of view. Platform motion carries the sensor along a line so a series of fields of view cover the search area. The relative amount of power arriving from each direction is recorded, but with somewhat less accuracy than in other types of systems. The record is displayed for human visual interpretation. Shapes and relative contrast in the record are used by the human interpreter to report to the system user what was found by the remote sensing system. Notice that the type of polarization is not measured, and the time of reception is primarily a navigational aid to locate the record in a geographic sequence.

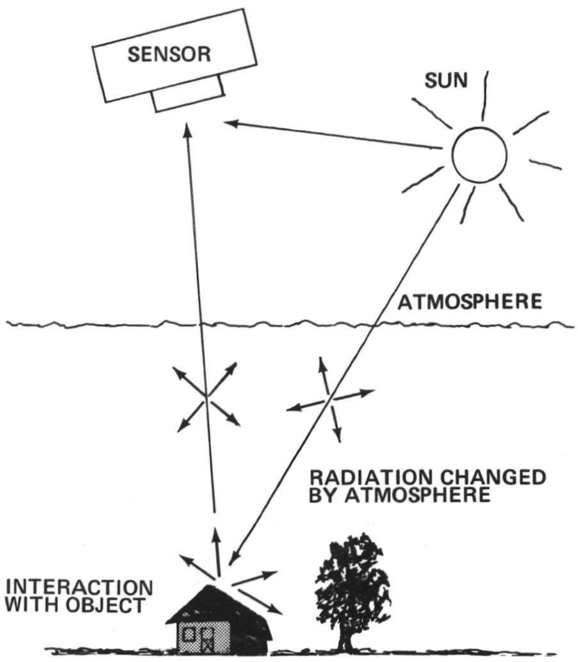

FIGURE 2. Operation of a passive sensor.

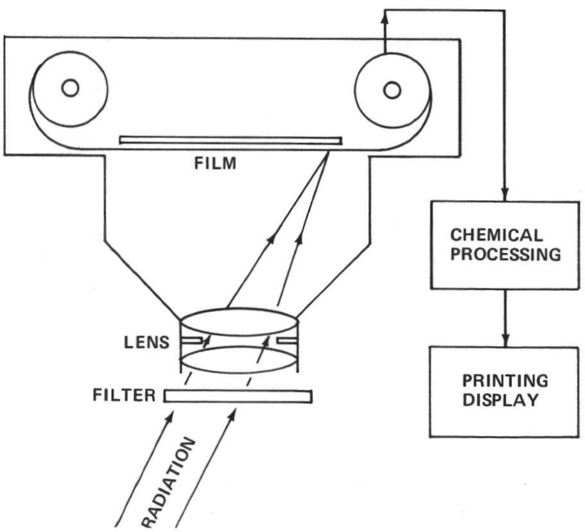

FIGURE 3. Diagram of a photographic camera sensor.

This same sensor can be operated in the stereoaerial photographic mode where the sequence of photographic fields of view overlap. The relative amount of power arriving from each position on the

ground is recorded twice—once from each of two different directions. Two overlapping recordings are presented to the human visual interpreter.

The interpreter then uses normal stereo vision along with visual aids to infer three-dimensional shapes and accurate locations of remote objects. The accuracy of recording the direction of arriving radiation by aerial mapping cameras is so great that almost all modern mapping is performed with this sensor. Other properties of the radiation, which are affected by the interaction with remote objects, are not measured. Identification of remote objects depends upon resolving shape and relative radiation quantity in the visible spectral range normally used by the human eye. If the objects are too small or too remote, their shapes are not resolved and the human visual apparatus fails to identify them properly.

The aerial camera, equipped with color film and operating in the stereo mode, measures the relative amount of radiation received in three broad spectral bands and from each of two different directions for each position on the ground. Six different measurements of the quantity of radiation that has interacted with every remote object are available. The color aerial stereo photograph presents essentially all data that can be used directly through human vision. The perception of color can be used to infer the identification of some otherwise unresolved remote objects.

The multiband camera extends the capacity of photographic sensors to record the quantity of received radiation in more than three spectral bands. A recording of the quantity of radiation from each remote position is made in as many as nine narrow spectral bands extending in wavelength from 380 to 900 nm. Photographic film does not readily record radiation with wavelengths longer than 900 nm. The terrestrial atmosphere will not propagate radiation with wavelengths shorter than 380 nm well enough for remote sensing. Since the human visual interpreter cannot at one time utilize more data than that from three spectral bands, preliminary data processing is required to obtain displays for interpretation. This form of data record is not suitable for sophisticated forms of computerized data processing. Consequently the full value of multiband camera data will not be easy to realize.

The video camera (figure 4) uses orthicon and

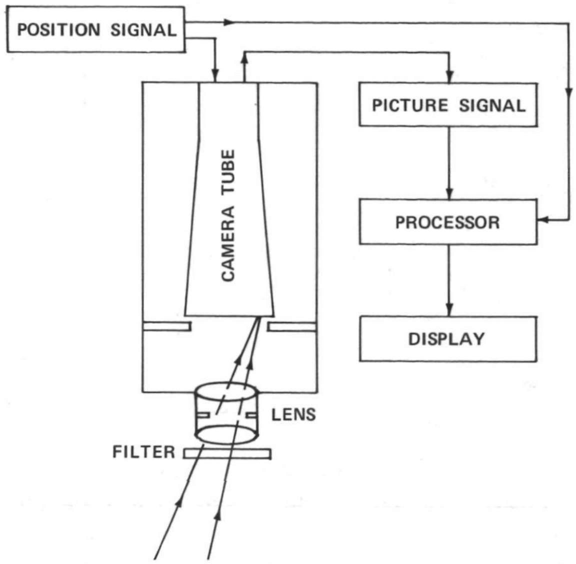

FIGURE 4. Diagram of a video camera sensor.

vidicon tubes. Its function is very similar to that of the photographic camera, but its recording of direction of received radiation is not as accurate. The received radiation forms an image on the detector tube in accordance with its direction of arrival. The quantity of radiation at each position in the image is translated to an electrical voltage or current which is sent to electrical amplifiers in time sequence. The time at which the image signal emerges from the amplifier corresponds to a specific location in the image, while the magnitude of the signal corresponds to the quantity of radiation arriving at that image position. Moreover, the resolution of images within the field of view is not as fine as can be achieved with the photographic camera using the same field of view. The video camera measures the same properties of radiation as the photographic camera, but with different accuracies. The major distinction of the video camera is that the data form is a time-sequence signal which is easily handled by electrical computer components. High-speed, economical data processing can be accomplished to aid interpretation. In addition, the time-sequence signal may be telemetered or tape-recorded for later use.

The optical-mechanical scanner measures the direction of arrival of radiation by a mechanical rotation of the optical components (figure 5). Only

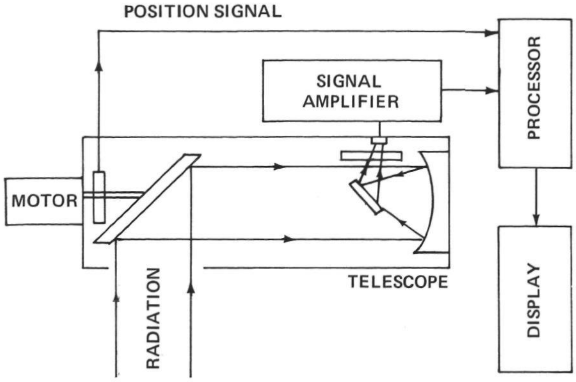

FIGURE 5. Diagram of an optical-mechanical scanning sensor.

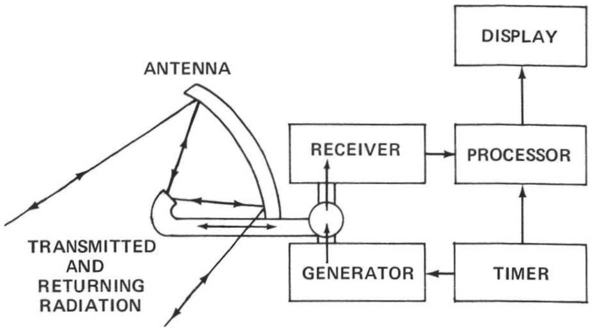

FIGURE 6. Diagram of a radar sensor.

the radiation arriving in the direction the optics are pointed is brought to focus on a small detector element. The resulting electrical signal, produced by the detector, corresponds accurately to the quantity of radiation from that direction. Electrical connections to the mechanical support of the optics produce signals corresponding to the direction of arriving radiation. In this way a set of time-sequence signals immediately suitable for electronic data processing equipment is obtained. The major advantage of the optical-mechanical scanner lies in the availability of small detector elements that respond to a very large spectral range of radiation. By properly choosing the detector element, one can measure radiation with wavelengths from 380 nm to 30 μm with an optical-mechanical scanner. Objects on the surface of the Earth thermally radiate much energy with wavelengths in the 3-to-15-μm range. Therefore the optical-mechanical scanner data can be made to correspond to the temperature of a remote object in this spectral band.

The multispectral scanner operates on the same principle as the optical-mechanical scanner. Radiation arriving in each direction is divided into a number of spectral bands by spectrographic apparatus, and the quantity of radiation in each band is detected by a separate detector element. Radiation in 20 or more spectral bands may be measured from each direction. The data is in an electrical form suitable for direct data processing by computer components. Identification of remote objects by their inherent spectral reflectance is occasionally feasible and economical with this kind of data.

Microwave radar (figure 6) is an active type of sensor. Consequently, microwave radar can measure with good accuracy the alteration in radiation by a remote object. A radar which measures a change in frequency between that generated and that received is called a Doppler radar. This change in frequency is a measure of relative radial velocity.

The most popular form of radar directs a pulse of generated power in a narrow beam and receives the reflection or echo from the same direction. The time between transmission of the pulse and arrival

Summary of radiant flux properties used by a side-looking pulse radar

Property	Generated radiant flux	Received radiant flux
Direction	Transmitted in narrow beam to the side of a moving platform	Same direction as transmission; less accurate than photographic camera
Spectral distribution	Monochromatic radiation at wavelengths from 1 to 10 cm	Same frequency as transmitted
Polarization	Determined by fixed antenna structure	As permitted by antenna structure
Time control	Emission of rapid sequence of pulses accurately timed	Time of reception accurately recorded to obtain range to reflecting objects

of the echo indicates the range to the remote reflecting object. Combining two modes of operation, a pulsed Doppler radar can measure the direction, range, and radial velocity of a remote object. The magnitude of returning radiation, when compared to that transmitted, measures the reflecting quality of the remote object. Polarization of the generated radiation may also be altered upon reflection, so a radar that measures polarization changes can assess an additional reflection property of the remote object. Signals received by the radar are in an electrical time-sequence form suitable for direct electronic computer processing.

Microwave radar combines the advantages of having a source of radiation at the command of the sensor operator and wavelengths that permit the penetration of almost every kind of cloud cover and weather (popular wavelengths being from about 1 to 30 cm). Microwave radar has the capability of measuring almost every possible alteration in properties of radiation as it interacts with a remote object (see table). Although its directional accuracy is not as great as that of the photographic camera sensor, the microwave radar makes a satisfactory geologic mapping sensor.

SUMMARY

The sensor is the radiometric part of a remote sensing system, and its data must be interpreted. Camera sensors excel in directional accuracy but are not suitable for interpretation methods utilizing sophisticated data processing at high data rates. Television cameras have less directional accuracy and spectral response, spanning nearly the same range as photographic cameras, but produce time-sequence data suitable for electronic processing. The optical-mechanical scanner has less directional accuracy, spans a very large spectral range with accurate quantitative measurements, and produces time-sequence data suitable for electronic processing. Microwave radar is an active sensor with less directional accuracy than the other sensors mentioned; but it can supply range, radial velocity, reflectance, polarization, and time-sequence data suitable for electronic processing.

The properties of received radiation depend upon an interaction with remote objects in accordance with natural laws. The full interpretation of remote sensor data requires a knowledge of how to make the connection between sensor-collected data and the identities of remote objects.

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Television Cameras

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Senior Scientist,
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Recent advances in the design of electron guns and signal readout systems for large image formats have increased the resolution of television cameras to 100 cycles/mm or 10 000 lines in a 50-by-50-mm format. Although similar to a normal television camera, the high-resolution camera uses a more sophisticated design to achieve a tenfold increase in resolution. The readout of 100 million picture elements from a single image requires changes in frame rate, operating modes, and signal processing. Camera design and operation are discussed in some detail and illustrated by photographs, and the performance is compared with that of photographic film cameras.

A television camera is essentially an extremely fast-scanning microphotometer, well suited for remote sensing of radiation from an aircraft or spacecraft. The optical image projected by a lens onto the sensor surface is converted directly into a time-ordered series of electrical signals for transmission to a remote location. The data can be displayed as a two-dimensional image, fed directly into a computer for data processing, or stored on magnetic tape for later use. The number of images obtainable from the camera is practically unlimited because the single sensor can be cleared electronically and used over and over again.

For a given field of view, however, the detail in normal television images is not nearly as fine as in a good photographic image. The detail possible is specified in television terminology by the total number of lines (half cycles) which can be resolved in the X and Y dimensions of the image format. The limited detail in normal television images is easily demonstrated with a test pattern. The reproduction by an excellent 600-line television system is shown in figure 1. The print in the maps and newspapers is completely blurred and unreadable. The numbers in the large circles multiplied by 20 give the resolution limit ($30\times20=600$ lines).

The detail reproduced by a 1000-to-1200-line television system (figure 2) is obviously much finer. The larger type is readable, but close inspection shows that a 1000-line image cannot compete with a direct photograph (figure 3). This photograph was taken with an f/11 lens on Panatomic–X sheet film and has a resolution limit of 45 000 lines. The format of the negative is 65 by 65 mm. The numbers in the small circle in the center and on the small wedges multiplied by 50 give the resolution. Inspection with a magnifying glass shows that the newspaper is not readable, as shown by the enlargement in figure 4. This performance represents good photography with a medium-sized camera, but it is exceeded with modern aerial cameras which have a resolution of 8000 to 10 000 lines in a 50-by-50-mm format (depending on contrast and lens quality) and can clearly resolve the print in the small newspaper.

One reason for the relatively low definition of commercial television cameras, even without restriction by a video frequency channel, is their small sensor format, which is only 12 by 12 mm in a 1-inch vidicon camera. A second reason is the lower information density expressed by the resolving power in cycles per millimeter. These deficiencies are not basic, and special high-definition television cameras with larger formats and a re-

FIGURE 1. Test pattern reproduced by an excellent 600-line television system (numbers in large circles multiplied by 20 give the TV line resolution).

solving power of 100 cycles/mm have been developed recently to achieve a total resolution of 10 000 lines in a 50-by-50 mm format. Figure 5 is a highly magnified section of the small newspaper in the test pattern reproduced by a camera with this format. The columns are 1 mm wide on the sensor, and the letters have a height of 28 μm. The granularity in this television image is lower than in high-resolution films.

THE HIGH-RESOLUTION TELEVISION CAMERA

The design of a high-definition television camera (ref. 1) providing uniform signal levels, low geometric distortion, a flat field of focus, and a uniform resolving power on the order of 100 cycles/mm in a large format has presented many problems. An axial section is shown in figure 6. The camera

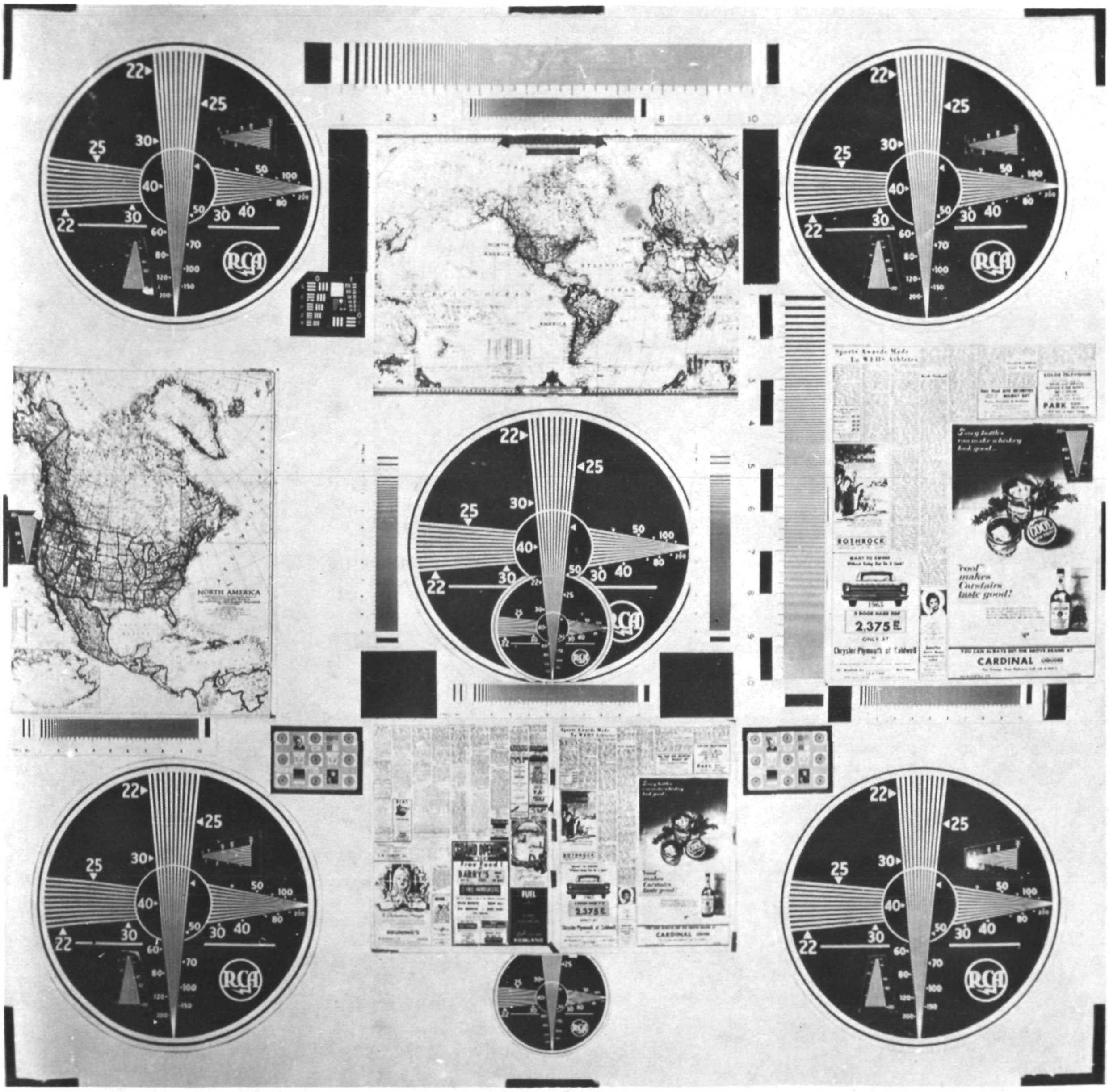

FIGURE 2. Test pattern reproduced by a 1000-line TV system.

contains a larger vidicon tube with electron multiplier, similar to an image orthicon. The camera lens forms an optical image on a sensor consisting of a large photoconductor, and the charge image is read out by scanning with an electron beam. Compared with a standard television camera, the signal readout system is considerably more sophisticated because it must provide performance equivalent to an optical microscope covering a large format.

From an electron optics point of view, the readout system of a television camera contains a source of electrons defined by the exit aperture of an electron gun located in the space L_0. This source is imaged (focused) by an electron optic (the focus coil) on the sensor. The electrons traverse at high velocity a long drift space L_1, terminated by a field mesh, and are decelerated in the short space L_2 before encountering the small charge potentials

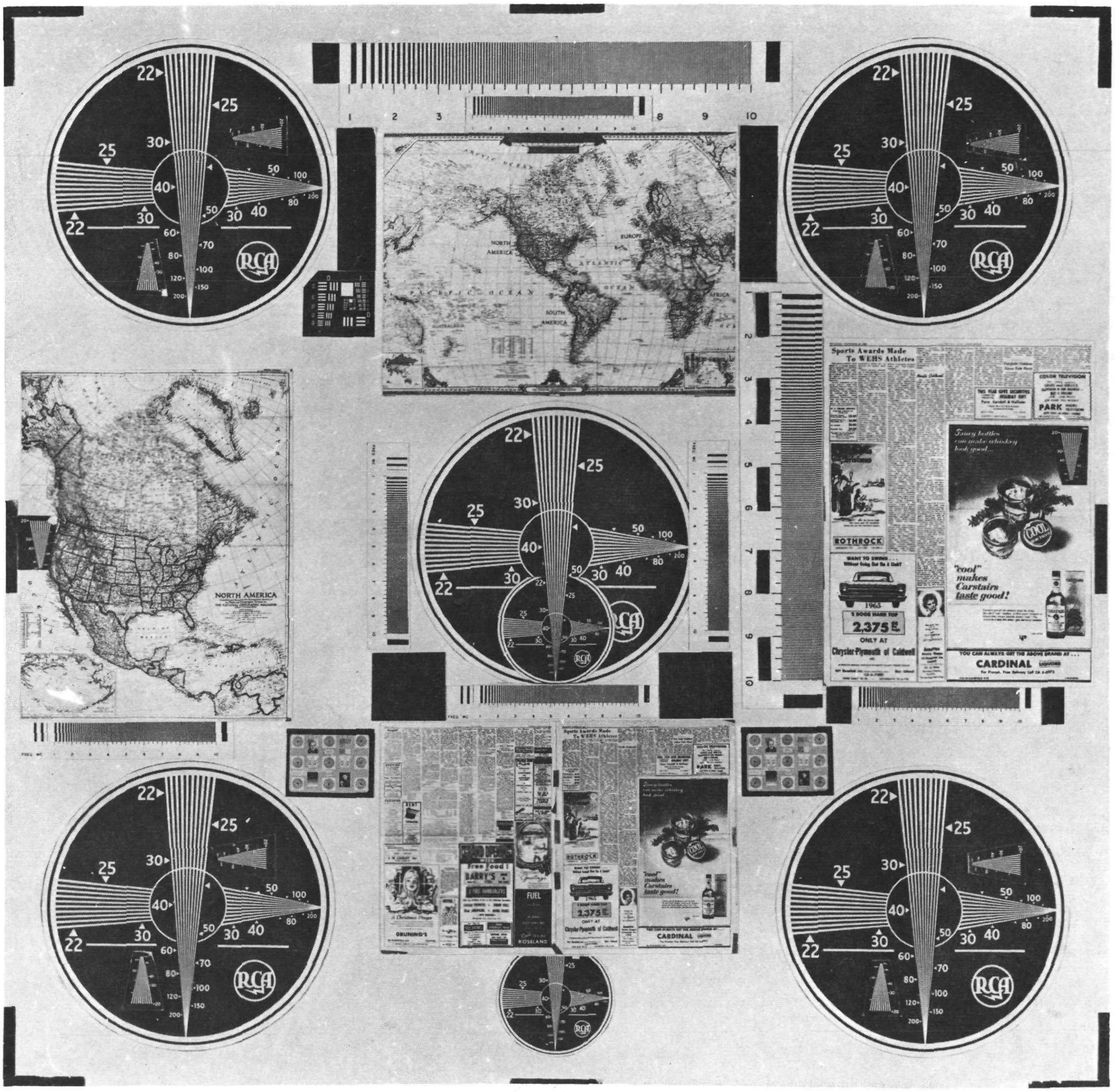

FIGURE 3. Photograph of test pattern made with f/11 lens on 65-mm square Panatomic sheet film with 4500-line resolution (numbers in small circle and on small wedges multiplied by 50 give the TV line resolution).

of the sensor. The electron beam is magnetically deflected in the drift space L_1 to scan the image format. The focused spot is intensity modulated by electron absorption at the sensor. The return beam retraces the principal path back toward the gun aperture, where it is slightly deflected to impinge on the first secondary emitter of the electron multiplier which surrounds the electron gun.

The simple focus coil of the normal television camera is replaced by eight coil sections which permit precise control of the magnetic field shape. Deflection aberrations are thus minimized and the focused image of the gun aperture is demagnified by a factor of 0.58 to obtain a smaller spot size at the sensor. Optimum conditions occur with four nodal (focal) points in the principal path. The electron

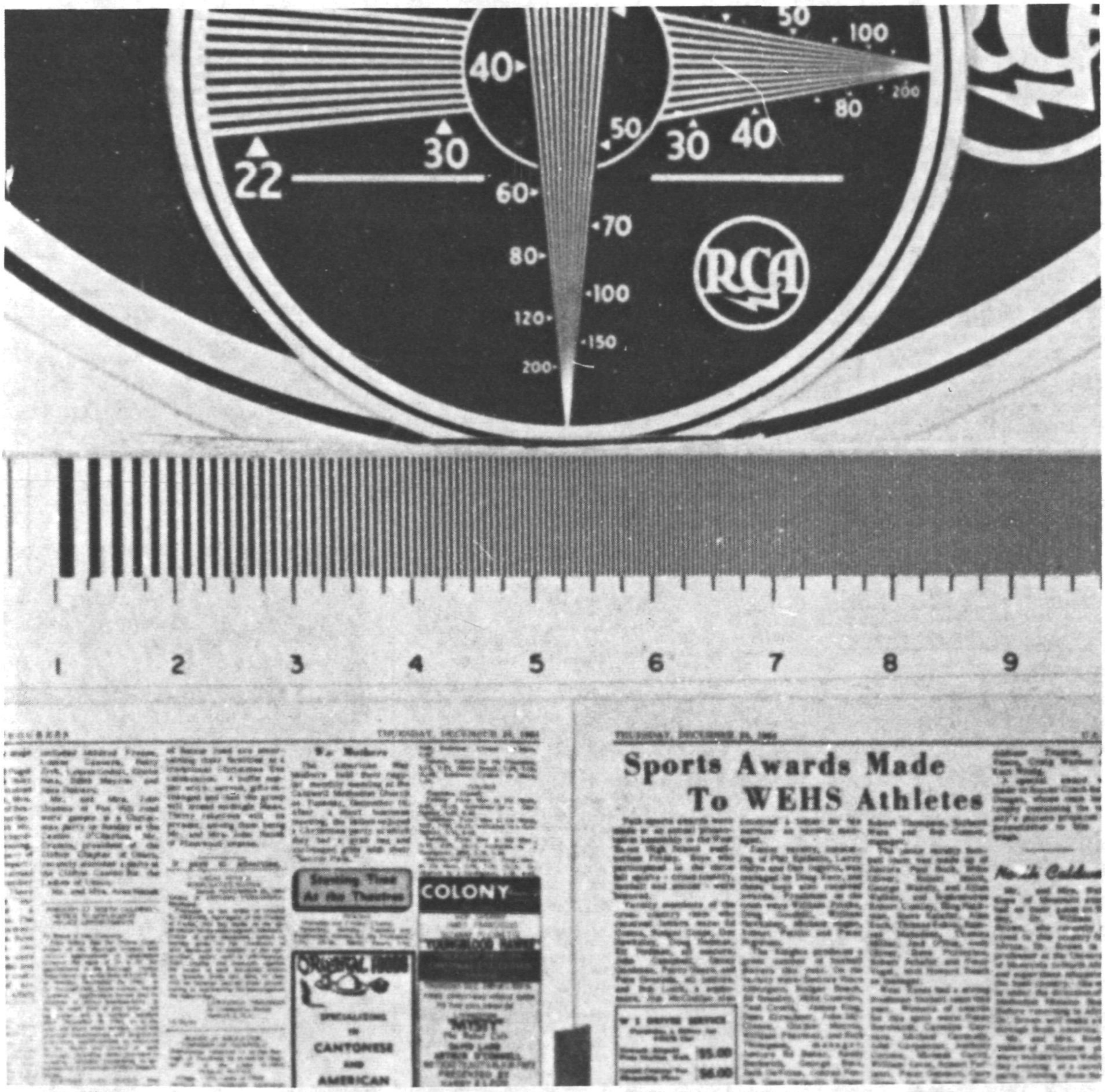

FIGURE 4. Enlargement of center section of figure 3.

gun is of special design because it must have a much smaller exit aperture and provide very much higher current densities in a finer electron beam than a normal camera tube.

Design requirements for a resolution of 100 cycles/mm are best described by modulation transfer functions (MTF). The MTF of the camera depends on the camera lens, the sensor, the field mesh, the electron optic, and the demagnified image of the gun aperture. The multiplier and video system have been eliminated as a factor by design for passbands up to 100 MHz. The design objectives for a resolving power of 100 cycles/mm are illustrated by figure 7. Curve 2 is the MTF of a perfect diffraction-limited f/5.6 lens, which represents the best state-of-the-art performance of modern large-

›orts Awards Made To WEHS Athletes

orts awards were ...n annual presen- ...embly in the West ...gh School audi- ...riday. Boys who ...ed in the three ... - cross country, ...nd soccer - were

... members of the ...untry team who ... letters were: Ed ...odger Coupe, Don ... Doug Hedman, ...ian, all seniors, ...ampbell, Danny ... Perry Neare, and ...eda, all juniors, ... Leith, a sopho- ... McClellan also received a letter for his service as varsity manager.

Junior varsity, consisting of Phil Epifanio, Larry Hulyo and Dan Ingerto, was managed by Doug Kerr, and these boys also received awards. Freshmen on the team were William Fricke, Doug Goodhill, William Hawksley, Michael Hogan, Robert Petillo and Peter Rigoloso.

The Knights produced a great number of football players this year. On the varsity were: Seniors Vince Albergato, Rodger Beach, Ed Beesley, Mike Costello, Paul Crotta, James King, Dean Kirschner, John McCleeve, Gordon Morris, William Pharmer, and Rich Thompson, manager. Juniors Ed Baker, Randy Beckwith, George Betz, Jack DeVries, Conrad Fenick, Gene Garguilo, Rodger Johnson, Carl Maffei, Mike Kalafer, George Mears, Joseph O'Brien, Charles Roveda, Francis Rice, Chris Unger, and Kent Smith, manager, and Sophomores Mike Furey, William Kaiser, Richard McCleeve, Robert Thompson, Richard Weis and Bob Connor, manager.

The junior varsity football team was made up of Juniors Paul Berk, Mike Oliver, Robert Smith, George Wakely, and Allan Walker, and Sophomores Robert Comley, Bing Heckman, Steve Kalafer, Alan Koch, Thomas Kukoc, Ramsey Mahadeen, Thomas Miller, Jack O'Hea, Andy Oliver, Steve Polverino, Robert Schafer and Peter Vogel, with Howard Heath as manager.

West Essex had a strong freshman football team this year. Winners of awards for this sport were: Peter Bernhardt, Carmine Carnaca, Michael Carmody, John Carpentier, Anthony Cottone, Michael Curry, William Eaton, Robert Ferlanti, Peter Gennaro, Gary Giess, Gary Hannon, William Kerr, Jeff Kuebler, George Lincoln, William Martin, Ron McAllister, William Miniutti, Joseph Mullen, Greg Park, Steve Scarano, Greg Varley, Charles Voelker, Byron Walker, Kenneth Walter, and managers Melvin Bellotti, Robert Dughi, and Albert German.

WEHS soccer team, co-champions of the state in Group II, came up with the best record of fall sports. Members of the 1964 soccer team who received varsity awards were: Seniors Bob Conkling, Paul Galusha, Harold Haberman, Glen Intile, Jon Knoop, Alvin Konner, Bruce Mc Kaba, Richard Meier, Tom Nelson, John Pullin, Greg Schneider, Jeff Smith, Gene Yarnchak and Bob Svehla; Juniors Jack Bruckah, Richard Goodman, Elmar Habermas, Fred MacNamara, Charles Partington, and managers Charles Bachellor and John Jehl.

Junior varsity consisted of: Juniors Fred Giltzow, Joe Jeremias, Roger Jones, Ralph Kelly, Richard Kurkewicz, Greg Lukemier, Tom Shelhamer, Bob Stevens, Kevin Wronko; Sophomores Russel Battye, Addison Truxton, Jay Vesce, Craig Warner and Kurt Wittig.

A special award was made to Soccer Coach Ralph Dougan, whose team had a trophy containing the varsity's picture prepared for presentation to him on stage.

North Caldwell

Mr. and Mrs. Walter Kope of Mountain avenue had as their guest on Sunday, Dr. William A. Brown, who recently arrived in this country from Africa. Dr. Brown is a professor at the University of Monrovia in North Africa and supervises education in the bush country. His work is under the direction of the Methodist Mission Board. Before returning to Africa, Dr. Brown will make a tour through South America.

Mr. and Mrs. Richard Nelson of Hillcrest place were holiday hosts Wednesday evening at a carolling party. Joining them for the joyous occasion were Mr. and Mrs. Benjamin Stanley, Mr. and Mrs. Robert Griffith, Mr. and Mrs. Oakley Roark, Mr. and Mrs. James Richards, Mr. and Mrs. Richard Wagner, Mr. and Mrs. Francis Dean, Mr. and Mrs. Ned Kehoe of North Caldwell, Mr. and Mrs. John Jacobsen of Cedar Grove and Dr. and Mrs. Joseph Fleming of Montclair. They all returned to the Nelson home late in the evening for refreshments.

Mr. and Mrs. Hyman Goldman of Mountain avenue were in the group who returned for a party after the recent presentation of Dickens' "Christmas Carol". The party was held for the cast and crew members at the Firemen's Building.

Miss Judith Goodman, daughter of Mr. and Mrs. Morris Goodman of Mountain avenue, returned home on Friday from Douglass College for the holidays.

Mr. and Mrs. Paul Bender of Pine place expect their son home for the holidays, from the University of Miami.

The Garden Club of North Caldwell has been busy making bedside arrange-

mother, Mrs. Alice Paules of Red Lion, Pa.

Mr. and Mrs. Robert Spinner of Deer Trail road with friends, Mr. and Mrs. Kenneth Diamond of Millburn, recently journeyed to New York to see the show, "Owl and the Pussy Cat."

Mr. and Mrs. Charles L. Jaeger of Grandview avenue are entertaining this evening Mrs. Jaeger's parents, Mr. and Mrs. Joseph C. Mergner of Belleville, who will remain overnight. Tomorrow, Mr. and Mrs. Jaeger will have as guests also Mr. Jaeger's parents, Mr. and Mrs. Charles Jaeger of Newark. Recent guests at the Jaeger home were Mr. and Mrs. Robert Kessler of South Acton, Mass., who formerly resided in Montclair.

Harry De Old, Jr., son of Mr. and Mrs. Harry De Old of Hillside avenue, is now at home for the holidays from Franklin College.

On January 14, Men's night will be celebrated by the Garden Club of North Caldwell. The annual Christmas tree burning will take place and following that a covered dish supper will be held at the Gould Avenue School. Speaker for the evening will be Roy De Boer of Rutgers University.

Mr. and Mrs. Wilbur Dean Fairley of Springfield, Mass., entertained Friday evening at a dinner party in honor of the bridal party of Miss Virginia Hamlin, daughter of Mr. and Mrs. Mahlon Hamlin of White Oak drive, who was

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FIGURE 5. Magnified section of newspaper image from the 50-mm charge image of the test pattern by a high-resolution TV camera.

aperture camera lenses covering a 50-by-50-mm format. The MTF of the sensor (curve 1), the image of the gun aperture (curve 3), and the field mesh (curve 4) must be of the same order (i.e., 65 percent at 100 cycles/mm). The electron optic (curve 5) is far better; it is in fact equivalent to a perfect f/1 lens. Therefore it has a minor effect on the overall product (curve 6).

Measured values are in good agreement with theory. Curve 7 was measured with a developmental camera tube containing a coarser (40 cycles/mm) field mesh and a larger gun aperture. The oscillograms in figure 8 show the vertical MTF measured with a sampling circuit. Figure 9 shows the CRT display of a resolution pattern reading directly in cycles per millimeter. The double-line circle is 2.5 mm in diameter. The visible resolution is limited by interference beats from the mesh, which should be

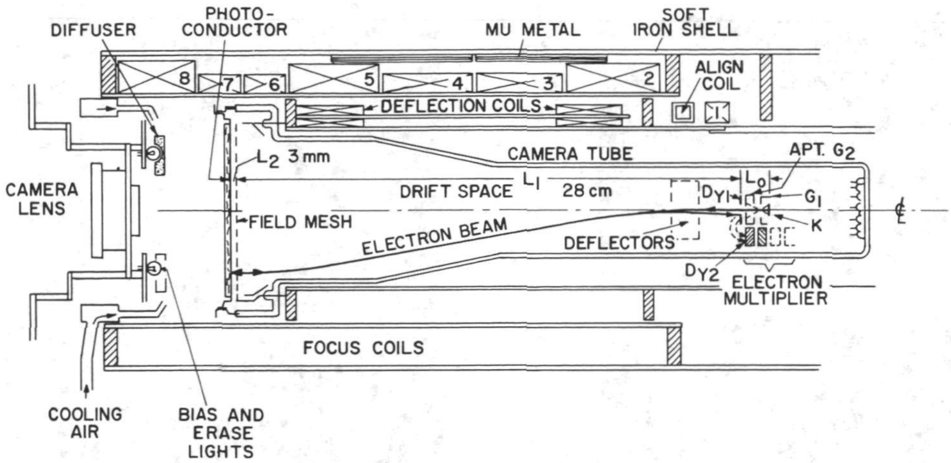

FIGURE 6. Axial section of a high-resolution TV camera.

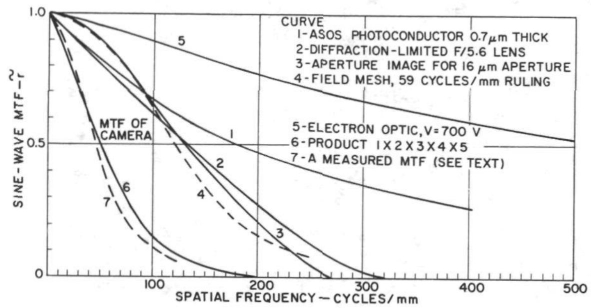

FIGURE 7. Modulation transfer functions of high-resolution TV camera.

finer. Flatness of field and uniformity of resolving power are essentially determined by the performance of the camera lens.

SENSOR CHARACTERISTICS

A high-resolution sensor must have a higher electron storage capacitance per unit area than normal television sensors to maintain a low noise level in very small detail areas. The compound antimony trisulfide (ASOS) photoconductor is at present the best solution because it combines a structure-free surface, high resolving power, and high storage capacitance (160 pF/mm^2) with good sensitivity. The relative spectral sensitivity is shown in figure 10. Silicon photoconductors are of great interest for certain applications because of their high sensitivity and extended spectral response. These new sensors are assemblies of individual photodiodes, and their resolution is therefore limited by a cell structure, which at present is 72 cells/mm. Cell densities of 140 per mm appear feasible and will give a resolving power of approximately 70 cycles/mm. The continuous ASOS surface has a resolving power of several hundred cycles/mm, as shown in figure 7.

The absolute sensitivity of a sensor is specified by its quantum efficiency (ϵ) because radiation energy comes in discrete packets or quanta of energy called photons. Thus, efficiency in converting photons to electrons (or to grains in a film) is basically a quantum value given by the ratio of the number of electrons stored in the sensor to the number of incident photons. Figure 11 shows that the quantum efficiency of the ASOS photoconductor increases rapidly as a function of the applied polarizing potential and that very high efficiencies are obtained when the sensor is charged to a high potential. Two dark-current curves indicate that moderate cooling of the sensor is necessary to reduce its conductivity in darkness, because dark-current charges would otherwise cause a high fog level.

CAMERA CHARACTERISTICS

The physical size of the camera is proportional to the format size. Two camera models have been built, one for a 2-inch return-beam vidicon (RBV) with 25-by-25-mm image format (5000 lines resolution) and a larger model for a 4.5-inch RBV with 50-by-50-mm format (10 000 lines resolution). Formats up to 100 by 100 mm appear feasible.

The larger camera is shown in figure 12 mounted

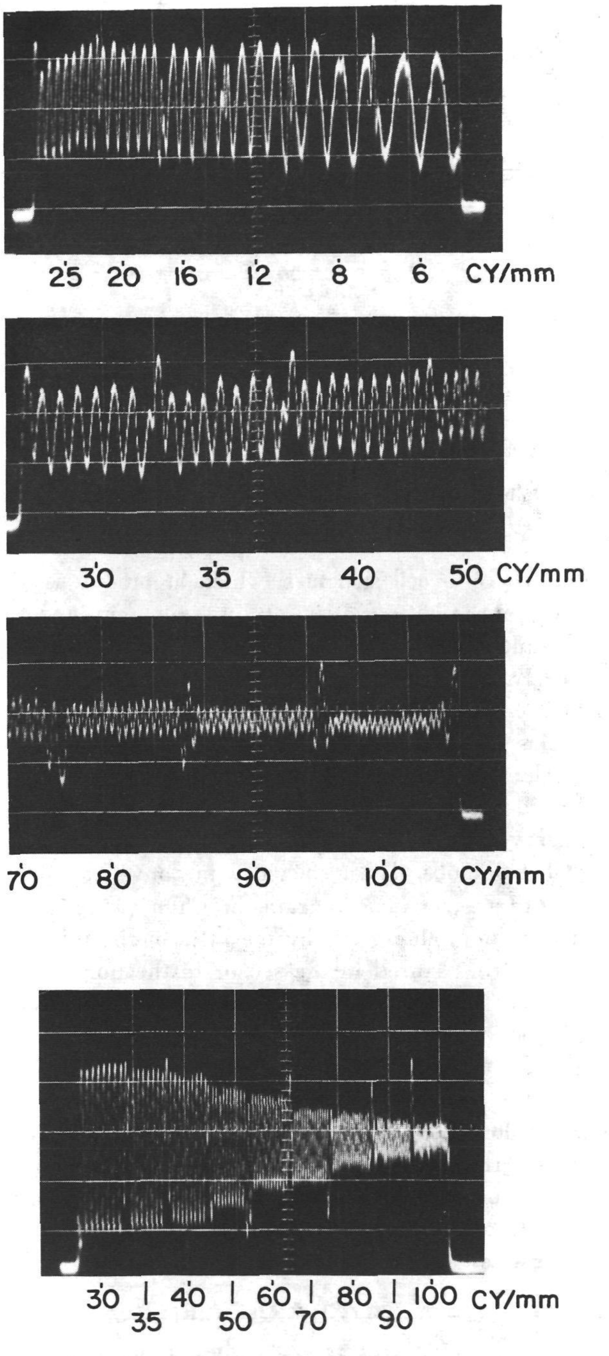

FIGURE 8. Oscillograms of sampled camera response in Y direction (bottom trace is of square waves; others are sine waves).

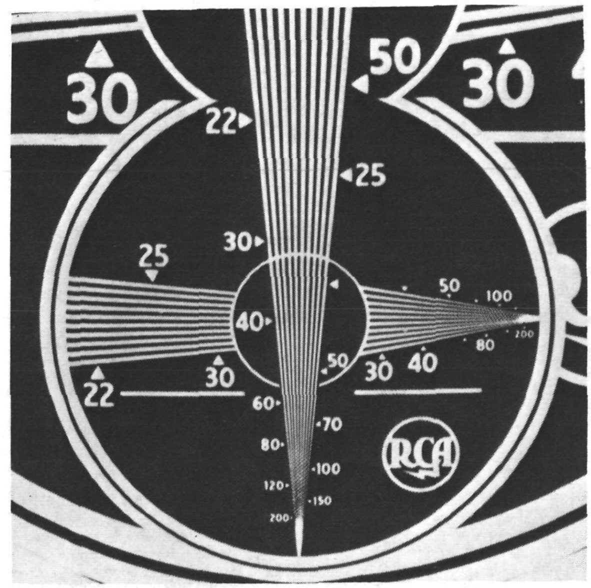

FIGURE 9. Magnified section of test-pattern display on CRT monitor showing 100-cycle/mm resolving power of experimental camera.

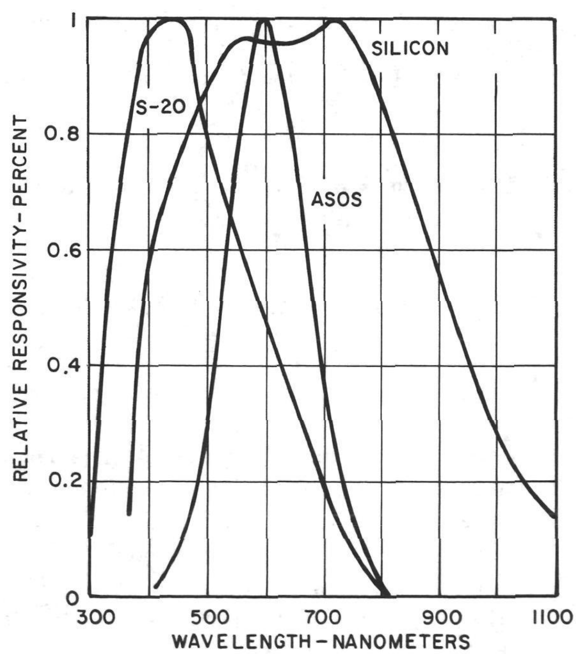

FIGURE 10. Spectral response of ASOS and silicon photoconductors and the S–20 photoemitter used in intensifier vidicons.

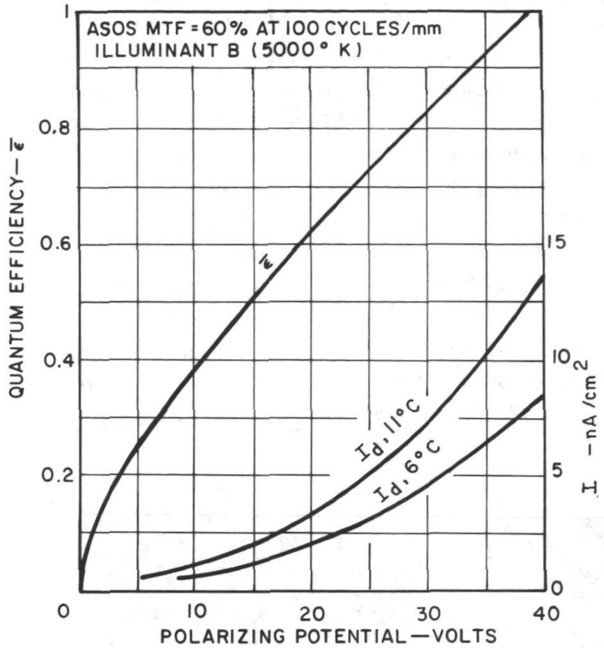

FIGURE 11. Peak quantum efficiency for sunlight and dark-current density of ASOS sensor as functions of polarizing potential.

FIGURE 12. Experimental camera (50-mm square format) in high-resolution test setup at RCA Electronics.

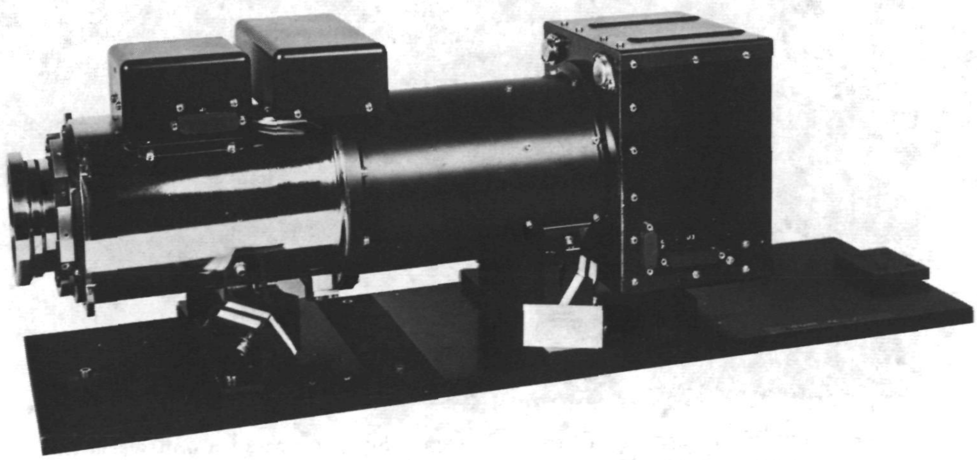

FIGURE 13. Feasibility model of small high-resolution TV camera (25-mm square format) for satellite use.

on the control unit of a high-resolution test bench. The smaller model is shown in figure 13. This model has been built for use in the Earth Resources Technology Satellites (ERTS), in which three boresighted cameras are exposed simultaneously and read out in sequence to obtain color information in three spectral bands. Figures 14 and 15 are photographs of dye-transfer prints. The color separation positives for these prints were made with the small RBV camera and a laser beam image recorder by scanning an aerial color photograph. The pictures do not show the full resolution of the camera because they are fourth-generation copies of the original scene.

Access Time and Operation

Fast access to the total information in a high-resolution image requires extremely wide electrical frequency channels and low-noise amplification by an electron multiplier. Even though video amplifiers have been developed for a frequency band of 100 MHz (i.e., a data rate of 200 megabits/s, including synchronizing periods), the total time required for scanning a single 10 000-line image is still 7/10 second. Since existing image recorders, tape machines, or computers cannot keep up with this rate, slower scan rates of 3 to 10 seconds per picture are used to reduce the data rate and the video frequency bandwidth.

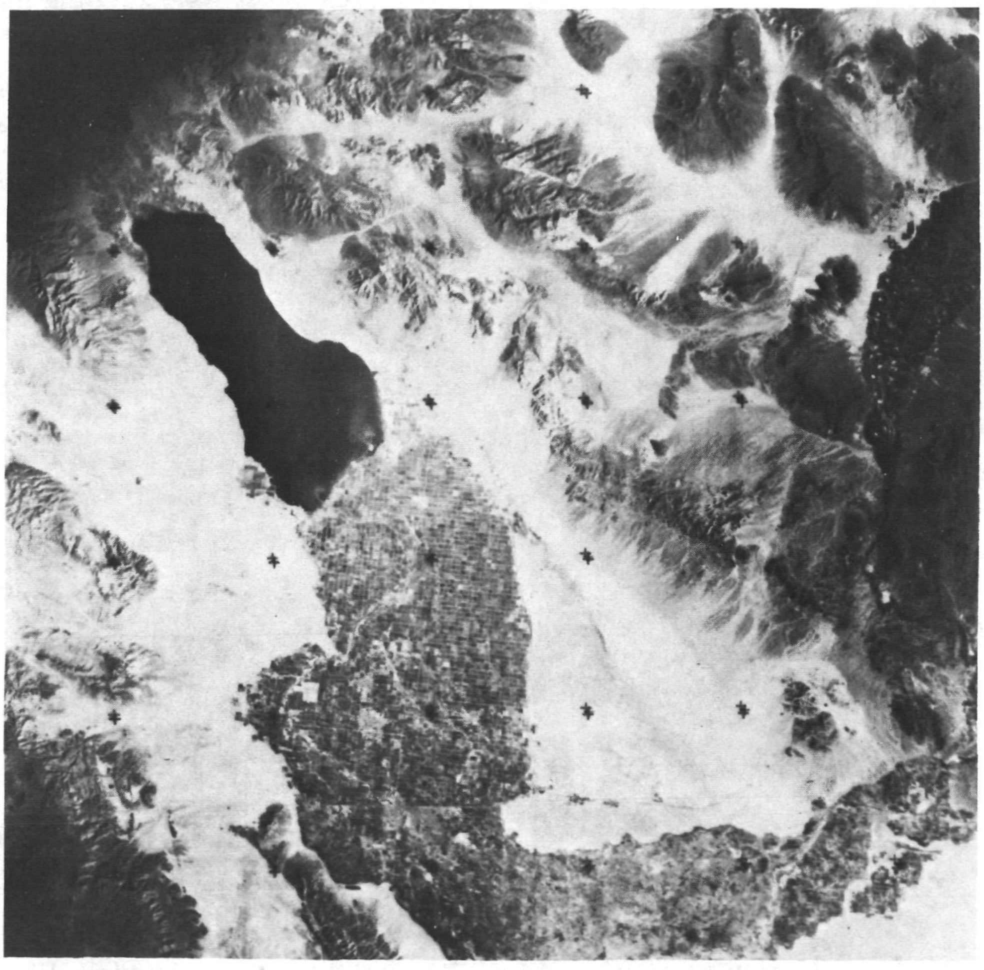

FIGURE 14. Reproduction of color IR space photograph by color separation with 50-mm RBV camera (25-mm square format) and laser beam image recorder (area shown includes Salton Sea and Imperial Valley, California).

FIGURE 15. Color photo of Globe, Arizona area reproduced in the same manner as figure 14.

It follows that a direct-view display of a live image with full definition is not feasible. The operation of the camera is more like that of a time-lapse motion picture with a slow frame rate.

Slow-Scan Operation

The exposure is timed by a shutter to obtain a sharp image and is followed by a single-frame readout in darkness. The sensor is then cleared of residual image charges by a high-intensity light flash (behind the lens) and recharged to polarizing potential to resensitize it for a new exposure. The sensor is recharged by scanning it in darkness with the electron read beam, which is increased to a very high current density to reduce charging time to a few seconds.* During the read phase, signals are recorded with a laser-beam image recorder as a positive image on a 23-cm square of film to provide a hard copy containing the full image definition. The color separation positives for the dye transfer prints (figures 14 and 15) are slow-scan recordings.

Fast-Scan Operation

A near-real-time direct-view image display on a high-resolution cathode ray tube is very useful for many purposes. The high sensor capacitance results in a long capacitive lag at fast scan rates, and several hundred copies of the same image can be read out from a single exposure at frame rates of 5 to 10 frames per second. With electronic gain and beam current controls, a low-noise flicker-free image of constant brightness can be displayed directly without a storage converter on a long-persistence phosphor (P–38) for at least 20 seconds. The resolution is of course limited by the band-

* The total storage capacitance of a 50-by-50-mm ASOS photoconductor is 0.4 to 0.8 μF. Current densities of 16 A/cm^2 have been achieved in the aperture of the electron gun.

width of the available video channel. The operating cycle consists of a short exposure followed by a continuous fast-scan read period and image display, which gives enough time to search for interesting detail. This viewing period is followed by a dead time of 5 to 10 seconds, in which the sensor is erased and resensitized for a new image. The dead time between images can be eliminated by alternate operation of two cameras to transmit an uninterrupted flow of still pictures.

Figure 16 is a photograph of a 10-frame-per-second display on the long-persistence screen of a 43-cm high-resolution picture tube.* This picture was made with the 50-by-50-mm television camera by pointing it at a paper print of a 23-cm square aerial photograph (a part of Philadelphia). The image resolution is limited to 1800 lines by a 60-MHz frequency channel. Finer detail can be displayed by reading out a selected small section of the sensor image. The 33-mm square area indicated in figure 16 is shown in figure 17. This electronic zoom magnification can be used for any part of the image, and the system can be designed for switch-over to slow-scan operation to read out the full definition in one copy.

ERROR CORRECTION

Although it is not conspicuous, the black level in these images is not completely uniform. Small errors in electrode concentricity, the ruling and electron transmission of the field mesh, and microscopic nonuniformities on the first dynode surface cause a spurious modulation of the scanning beam which results in shading or scratches. This black-level distortion can be cancelled by an error signal, which is generated simply by a readout without exposure.

In a slow-scan system, the error signal for one picture frame can be recorded to yield a correction mask for succeeding pictures, or even better, electrical error signals are stored in a video recorder before taking a series of pictures, and are then added in synchronism with reversed polarity to the video signals of subsequent images to cancel the black-level error.

Error correction in a fast-scan readout can be achieved by an alternate field readout of normal signals and reversed error signals (obtained by target blanking), as illustrated by figure 18. These signals are superimposed sequentially by storage in a long-persistence display screen. The uncorrected and corrected images are shown in figure 19. The correction of a very nonuniform black level is illustrated by figure 20.

SENSITIVITY AND RESOLVING POWER

A comparison of the sensitivity and resolving power of photographic and television cameras on an absolute scale is of interest. Real imaging systems are far from realizing the theoretical limit of the resolving power inherent in the quantum nature of the radiation incident on the sensor, either because of a low quantum efficiency (ϵ) in the primary photon conversion process, a low readout efficiency, or losses in the modulation transfer through the camera and the signal developing process. The resolving power of a system can be computed with good accuracy for the standard three-bar test object shown in figure 21 from the square-wave transfer functions and noise sources of the system. A threshold signal-to-noise ratio k of 3.6 is necessary to resolve a particular pattern frequency in a single image (ref. 2). Signal and noise are determined in principle by a particle count in the area of one test object bar. The signal-to-noise ratio increases for higher particle densities and is therefore a function of the radiation energy and the number of photons incident on the sensor during the exposure time. The absolute photon-limited resolving power of the radiation without degradation by a lens is shown in figure 22 by curve 0 in cycles/mm as a function of the mean exposure $\overline{E}$ expressed in lumen-seconds/m^2. This absolute limit was computed for high-contrast test objects illuminated by sunlight for the wavelength range $\Delta\lambda$ between 400 and 700 nm. Because of the modulation loss in a real camera lens, increasingly higher exposures are required for higher resolving power frequencies, as shown by curve 1 for a perfect f/5.6 lens. This lens is used as a standard to compare different cameras. It follows that the maximum resolving power of a camera is limited by the MTF of the lens and not by the exposure. The quantum loss in the sensor and inefficiencies in the modulation transfer in the camera require a further increase in exposure to maintain a given resolving power and introduce a lower maximum limit (ref. 3).

* The time constant of the P-38 phosphor is 0.47 second.

FIGURE 16. Full-format direct-view image of 23-cm square aerial photo reproduced with 50-mm high-resolution camera (resolution limited by bandwidth to 1800 lines).

FIGURE 17. Detail in 33-mm square area indicated in figure 16 brought out by underscanning.

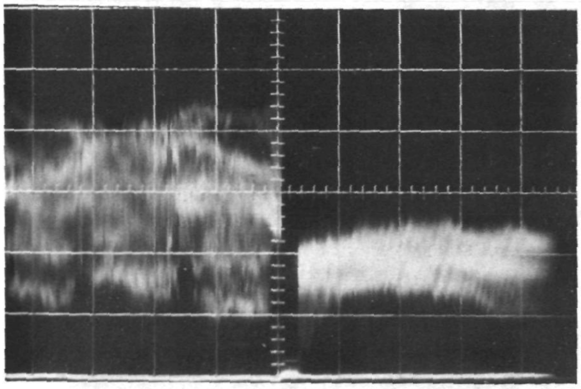

FIGURE 18. Oscillogram of video signal and error signal fields.

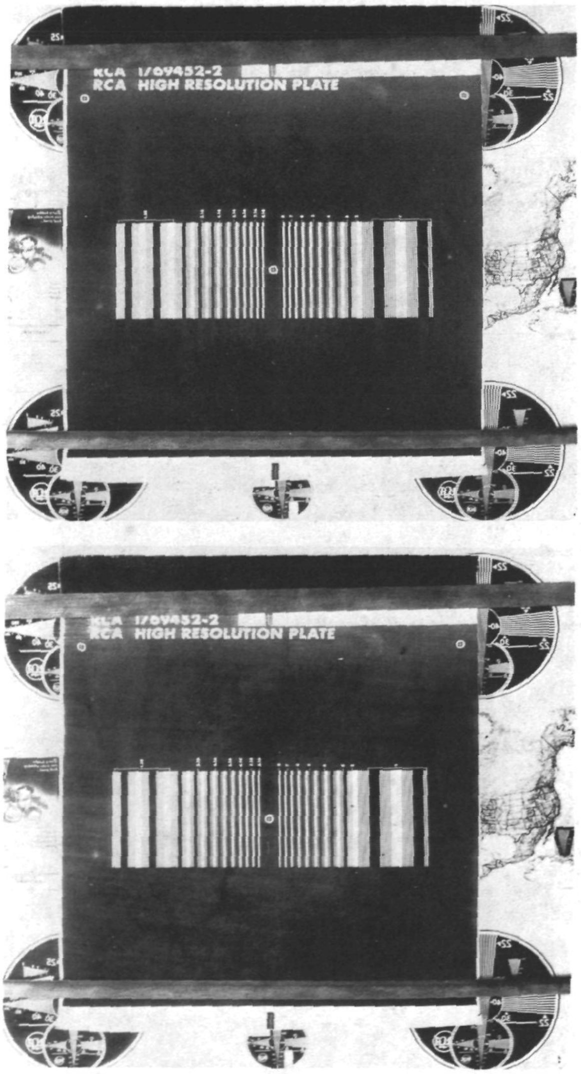

FIGURE 19. Electronic black-level error correction (top, uncorrected image; bottom, corrected image).

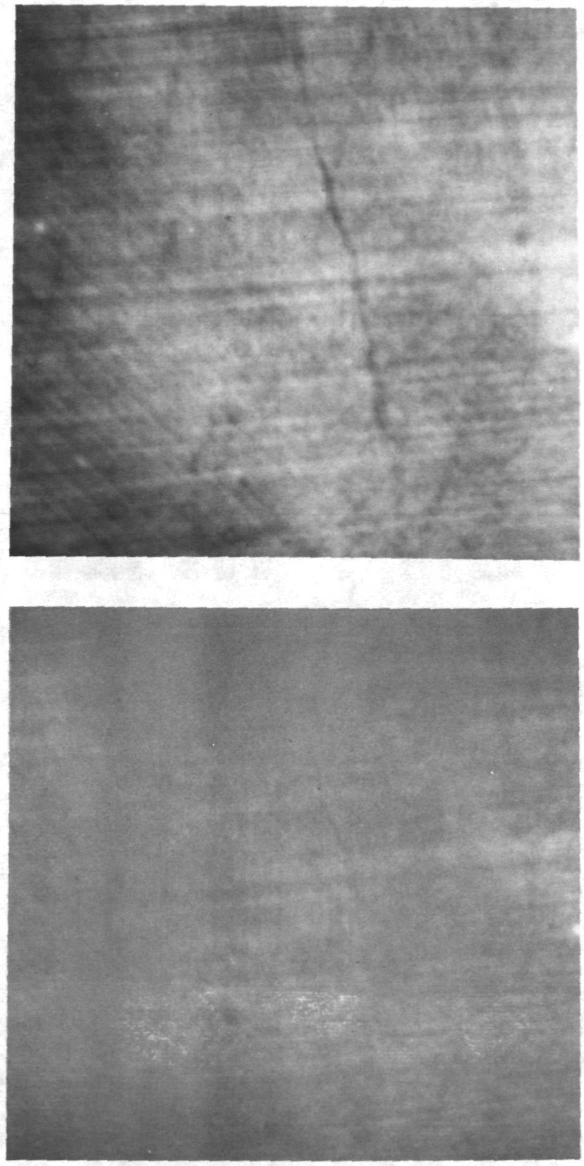

FIGURE 20. Correction of a very nonuniform black level (top, uncorrected; bottom, corrected).

The low quantum efficiency of photographic emulsions (less than 1 percent) and MTF losses by the grain structure move the resolving power limit of photographic films to curve 2(a), which closely indicates the maximum resolving power of all film types without degradation by a camera lens. The circles indicate values for several film types. A perfect f/5.6 camera lens decreases these maximum values to curve 2(b). The resolving power functions of specific film types are limited to a specific ex-

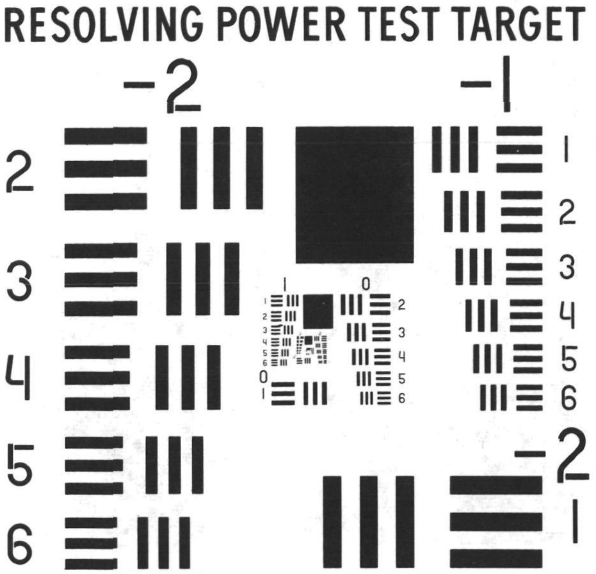

FIGURE 21. Standard three-bar resolving power test object.

posure range and reach the maximum resolving power given by curve 2(b) at particular exposure values. An aerial exposure index scale (Eastman Kodak values) appears at the top of the graph.

The resolving power functions of television cameras have been computed similarly. The sensitivity expected from the high quantum efficiency of the sensor is not realized because of inefficiencies in the readout system, beam noise, and the large MTF loss in the camera, including the f/5.6 lens, which levels out the resolving power functions at higher exposures. Curve 3(b) represents the performance of state-of-the-art high-resolution cameras; the performance represented by curve 3(a) has been obtained with camera tubes having a finer electron beam. The sensitivity of the television camera can be extended to much lower exposures by adding an image intensifier, as shown by curve 4 for image intensifiers with a photon gain G of 50. Much higher gains are obtainable with silicon-intensifier targets (SIT) yielding the very low-light-

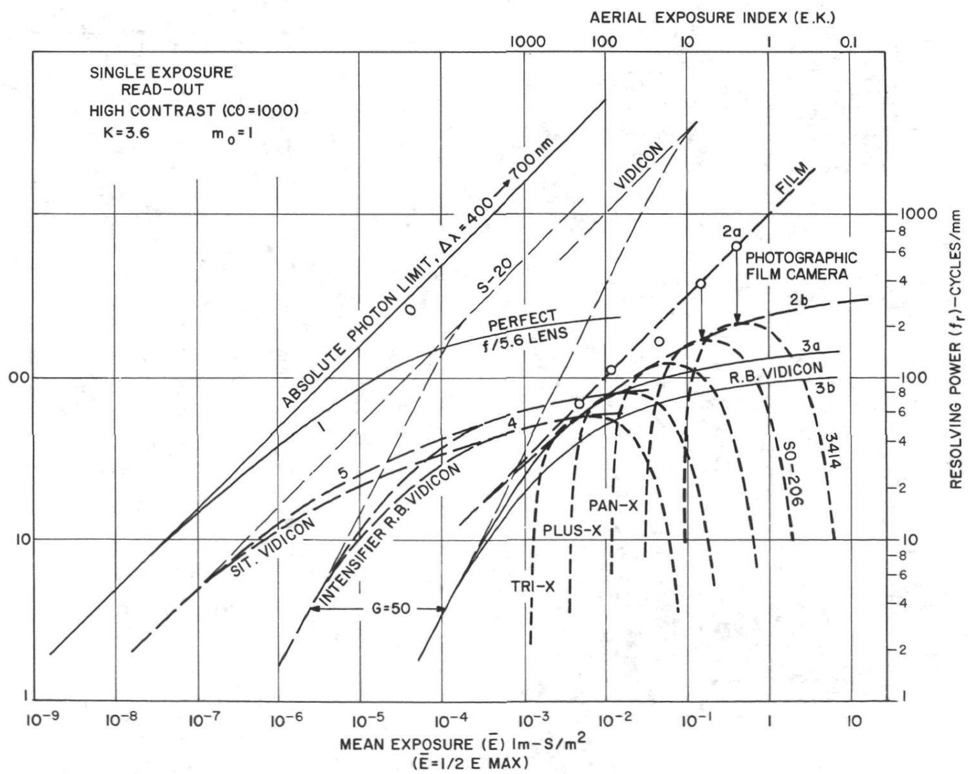

FIGURE 22. Quantum limits and resolving power of photographic and TV cameras with perfect f/5.6 camera lens, for high-contrast three-bar test objects.

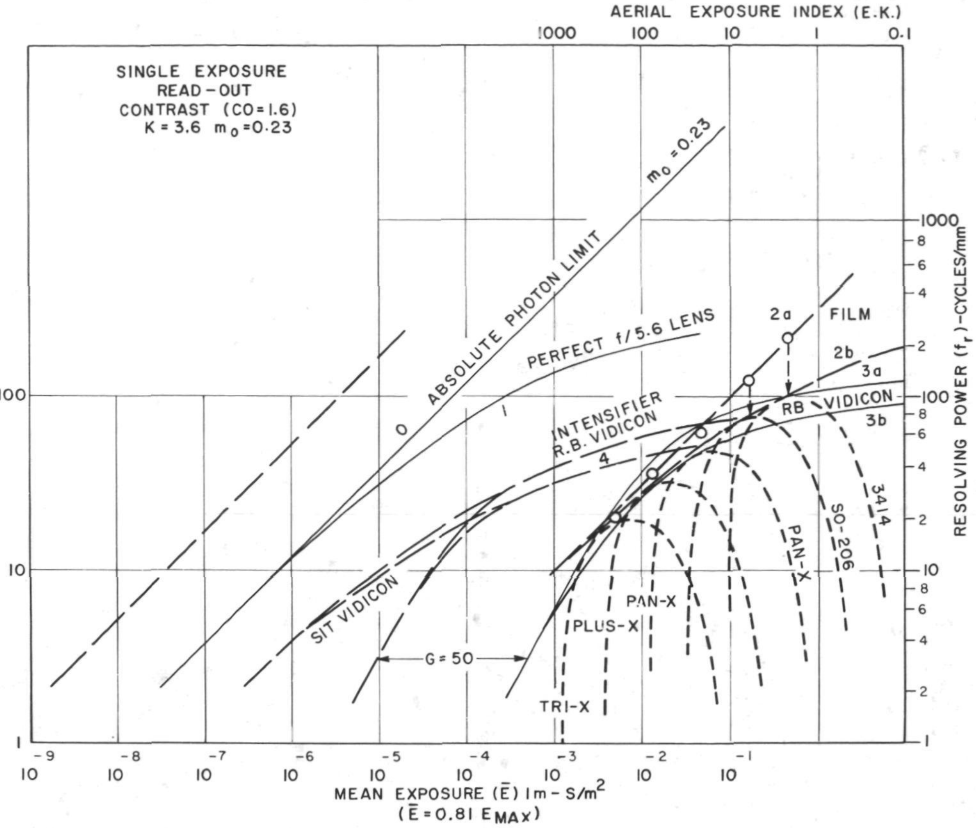

FIGURE 23. Quantum limits and resolving power of photographic and TV cameras with perfect f/5.6 camera lens, for a test object contrast ratio of 1.6:1.

level performance shown by curve 5. The maximum resolving power of intensifier vidicons is lower because of the additional modulation loss in the intensifier. Thus, a high-resolution TV camera (curves 3(a) and 3(b)) covers the exposure range of all film types. The photographic camera has a higher maximum resolving power for high-contrast objects. This advantage is no longer gained at lower contrasts, as shown by figure 23 for a contrast ratio of 1.6 to 1, which corresponds to an input modulation m_0 of 0.23. Because of the decrease in input modulation (m_0), all limit functions move to higher exposures. (The factor is $1/m_0^2=19$.) The resolving power functions for individual films move downward because of the fixed grain number and exposure limits of a film type, whereas the television functions are displaced horizontally to higher exposures. Thus, a high-resolution television camera is more sensitive and can match or exceed the performance of photographic cameras at medium and low contrasts.

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Aerial Cameras, Aerial Films, and Film Processing

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Any discussion of the aerial camera must of necessity contain information regarding aerial films and aerial film processing, for the aerial camera is merely the instrument used to procure a precision photograph. An unbroken continuity of quality assurance procedures is mandatory from manufacture of the original aerial film through its use in the aerial camera, its photographic processing, and reproduction. A logical approach to the development of aerial photographic expertise, starting with the use of simple, low-cost systems, is outlined.

For over a hundred years man has been capable of leaving the surface of the Earth accompanied by the camera. A century ago, both his aerial vehicle and aerial camera were quite rudimentary. Figure 1 is a reproduction of a photograph made in 1860 by C. W. Black aboard a tethered balloon some 300 meters above Boston, Massachusetts. It is the first recorded aerial photograph taken in the United States and certainly one of the very first ever taken. The "wet plate" was immediately processed by Mr. Black and his eager young assistants. One assistant, Oliver Wendell Holmes, recorded in his diary, "This is indeed a most remarkable thing." Although Holmes did not achieve greatness in the photographic profession, he did become a most distinguished man of letters and a long-time Justice of the Supreme Court of the United States.

It truly was a most remarkable thing. Few modern engineering works involving the utilization of the surface of the Earth have been accomplished without the use of aerial photography.

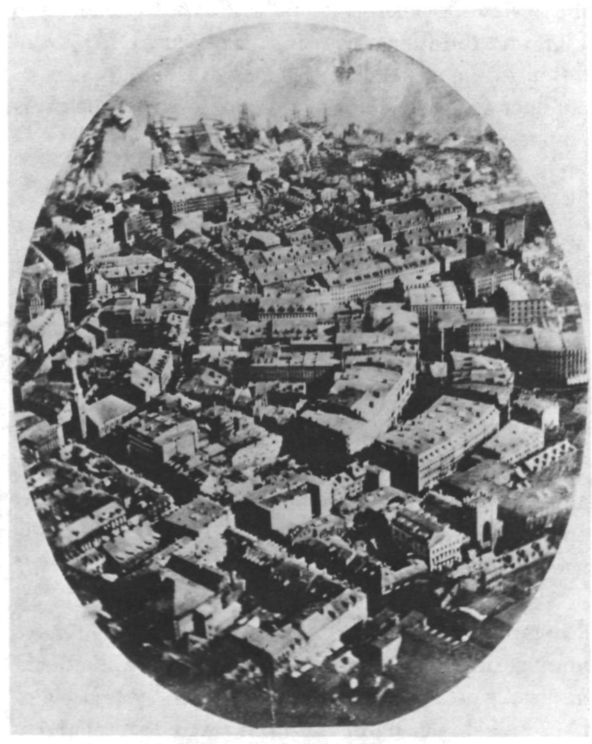

FIGURE 1. Aerial photo of Boston, Massachusetts, taken in 1860 (courtesy GAF Corp.).

Aerial photographic technology was quite dormant until the powered aircraft became a fairly efficient platform. Early aerial cameras were heavy and generally unreliable. Many used photographic emulsions on glass plates. Flexible films of nitrate base were highly flammable and dangerous in aircraft. Optical-mechanical devices used in mapping projects were rudimentary and far from precise.

But, as the needs for accurate information grew, greatly improved cameras, films, processing equipment, and plotting devices were developed.

In the past few years, it has become apparent that the aerial photograph is an essential tool working in concert with a multitude of remote sensors designed to secure information in other portions of the electromagnetic spectrum. The very limited portion of the spectrum available to photography practically coincides with the recording ability of the human eye. The unique combination of Earth-orbiting spacecraft or high-efficiency aircraft, photography, and other remote sensors has started a true renaissance in the ability to conduct detailed, comprehensive, and highly productive Earth resources surveys.

Actually, any camera used from an aircraft is capable of recording valuable information. It is a grave mistake, however, to attempt to secure information beyond the capabilities of any part of the system. It is absolutely mandatory that we discuss the system concept (that is, the aerial camera, the film, and the film processing techniques). Any violation of the system concept negates your ability to conduct accurate studies. This point cannot be overemphasized.

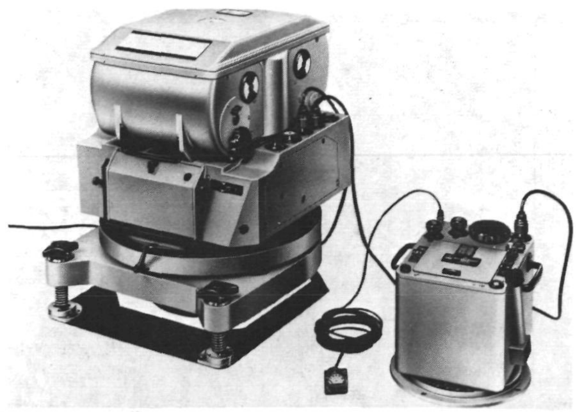

FIGURE 2. Zeiss RMK 15/23 aerial camera (courtesy Carl Zeiss Co.).

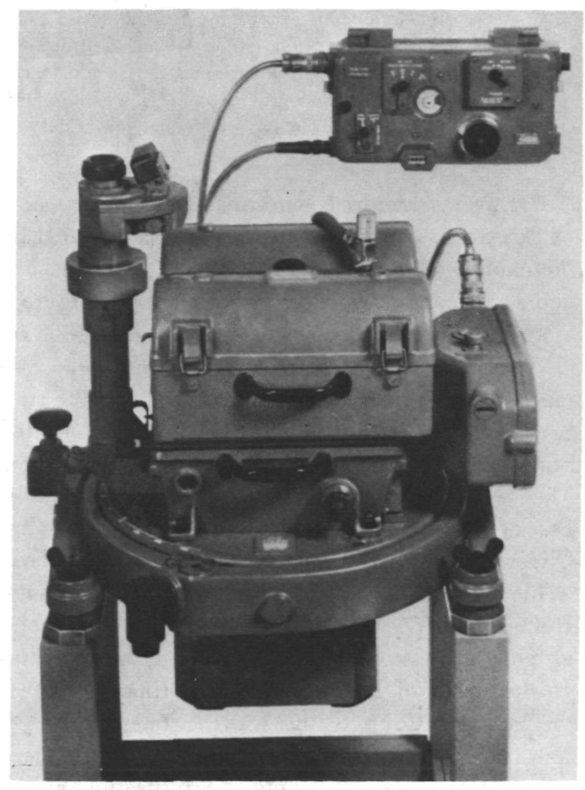

FIGURE 3. Wild RC–8 aerial camera (courtesy Wild-Heerbrugg Co.).

THE AERIAL CAMERA

Aerial cameras are available in numerous sizes with a variety of film formats, focal lengths, precisions, spectral responses, and costs. Selection depends primarily on the type of information the user wishes to secure. Typically, the conventional aerial camera has a focal length of 150 mm, a square film format of 23 cm, and uses film in lengths of 50 to 75 meters. The combination of focal plane flatness and lens distortions will be less than 0.01 mm. Examples of such cameras now in general worldwide use are shown in figures 2 and 3.

A careful study of all aerial cameras should be accomplished prior to final selection. If you have no experience whatever in aerial photographic techniques, you should start with simple system—perhaps a single-engine aircraft and a relatively inexpensive aerial camera such as the 70-mm Hasselblad EL (figure 4). Such equipment permits your aircraft pilots and cameramen, your photographic laboratory personnel, and your user-geoscientists to increase their level of expertise a great deal with a minimal investment of financial resources. As the level of technical competence improves, you should then consider more sophisticated systems and techniques up to the level required to accomplish your objectives (figures 5 and 6).

FIGURE 4. Hasselblad EL 70-mm data camera with reseau plate and interchangeable lenses (NASA photo).

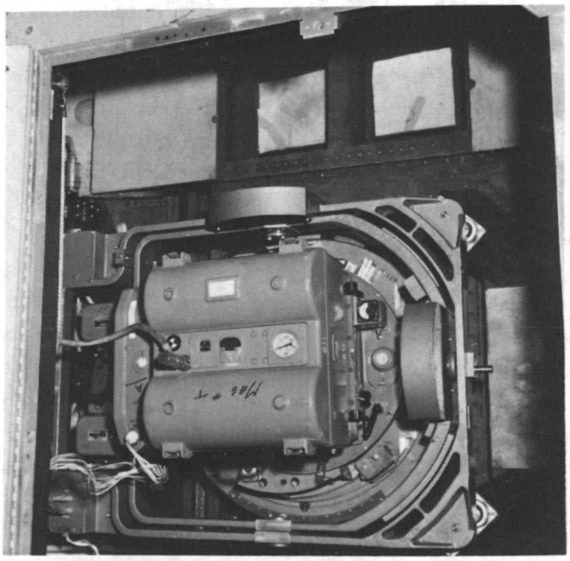

FIGURE 5. Wild RC–8 aerial camera mounted in aircraft.

FIGURE 6. Aerial photographer operates intervalometer for aerial cameras.

For high-quality aerial surveys using good commercially available cameras, you must give serious consideration to the following camera characteristics.

Focal Length

Aerial cameras are available with focal lengths from about 25 mm to more than a meter. The focal length governs the scale relationship of the actual size of the subject to its image size on the exposed film. For example, a camera with a focal length of 500 mm at an altitude of 1 km would yield an image scale of 1:2000. A ground distance of 100 meters would be 5 centimeters (or one part in 2000) in the photographic image. Longer focal lengths do indeed increase your image size, but not necessarily your ability to detect information.

If you wish to secure photographic coverage of large areas but are not greatly interested in absolute detail, you should use a short-focal-length lens. Because fewer flightlines will be required to obtain the desired coverage, savings can be made in costly aircraft operation hours. Additional small savings result in costs of film and processing. Conversely, if you need to obtain fine resolution, you will require a camera with a longer focal length. In many cases you may be attempting to secure various types of information simultaneously, and therefore both types of cameras will be required.

The conventional aerial camera (150-mm focal length with a 230-mm square format) is considered a wide-angle camera. The cone of light passing through the lens is approximately 90 degrees. The so-called superwide-angle aerial camera with a field of view of about 120 degrees uses the conventional 230-mm square format but has a lens with a focal length of approximately 88 mm. The user should also consider cameras with interchangeable lenses, which provide the ability to use various focal lengths with one camera body.

Resolution of the Image

The quality of the lens is of major importance (figure 7). It should have a high factor of light transmission (that is, ability to permit all or nearly all the available light reflected from the subject to reach the film). It should be a fairly fast lens (that is, have the ability to transmit sufficient light to the film in a relatively short exposure time). Lenses of f/4.5 or f/5.6 are generally considered fast enough for most aerial applications. Basically, the f-number is a computation of the ratio of the calibrated focal length of the system to the diameter of the lens aperture. For example, an f/10 aperture would be about 10 mm for a 100-mm-focal-length lens. Several camera manufacturers are beginning to use T-numbers instead of f-numbers. The T-number system additionally takes into consideration the transmission capabilities of the lens system.

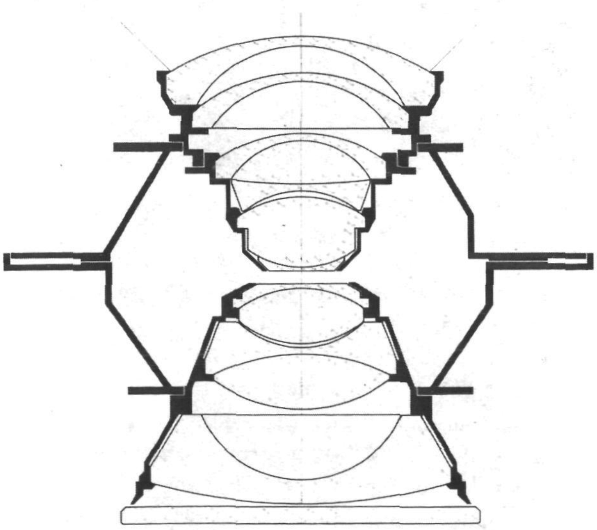

FIGURE 7. Modern aerial camera lenses are complicated and precise. Shown: the new 150-mm Universal-Aviogon II f/4 lens by Wild-Heerbrugg.

The true distortion-free lens is not yet a reality. Optical distortions are the result of many factors which cause deflection of a light ray from its true and correct location on the film. For precise mapping, residual distortions of less than 0.01 mm are required. When information to be secured does not require such precision, lenses of greater radial and tangential distortions can be tolerated, and they usually have superior resolving power. The flatness of the focal plane can also affect the total optical ray distortion. The degree of perpendicularity of the focal plane to the optical axis is another factor which must be considered.

The above considerations all affect the ability of a camera to record a specific image. In addition, the optical precision of the lens elements plays a very important part in the ability of the lens to resolve a subject. In total, the resolution capability can be expressed as the system's ability to distinguish two distinct line pairs of a specified width, with equal spacing, at varying contrast levels. The resolution will vary in different parts of the lens (best at the center) and with different levels of contrast.

Generally, you should not consider lenses that demonstrate static resolutions below 40 line pairs per millimeter at a contrast ratio of 1:1000 on the optical axis of the lens. If you are solely interested in information and not geometric fidelity, lenses of 80 or more line pairs per millimeter should be considered.

Spectral Responses

The modern aerial camera took on its basic design before the advent of practical and economical utili-

zation of color films. It was not necessary then to manufacture lenses with polychromatic capability. A yellow filter was usually incorporated into the optical system to subdue the response to near ultraviolet and blue light, which is usually present due to suspended aerosols and other particulate matter found in the atmosphere.

In the past few years it has become economically feasible to use aerial color films. The beautiful color photographs of the Earth secured by Gemini astronauts made this fact dramatically clear. If your Earth survey plans call for the use of aerial color films, it is absolutely necessary that you use a polychromatic (color-corrected) lens in your aerial camera.

RESEAU CALIBRATION

There are aerial cameras which contain in the optical path, usually adjacent to the focal plane or film surface, a glass plate with fine line markings (usually crosses or dots) which are positioned very accurately. These calibration marks, called reseau marks, appear on the exposed film. Generally, they are located at 1-centimeter intervals, with a central mark coincident with the optical axis of the lens system. These marks, to be of any significant value, should be at known positions and accurately located within ± 0.0025 mm. The camera manufacturer should provide a very complete document regarding his calibration of the reseau mark positions and the precision capabilities of the measuring instruments used to generate such data.

It should be emphasized that a reseau calibration is not necessary for most work to be done with aerial cameras. However, if you require very accurate knowledge of the deformation of each exposure of film due to mechanical manipulation within the camera or film processor, or need to compute any movement of the emulsion with relationship to the film base during processing, or plan to perform very accurate aerial triangulation surveys, the reseau calibration is an invaluable asset.

Some aerial cameras have crosses, dots, or other identification marks in the corners or at the center of each side of the format. These fiducial marks are of great value in locating the optical axis of the system and in determining film deformation. For precise cartographic work, fiducial marks or a reseau are a requirement.

FILTERS

Usually filters will be introduced into the optical paths of aerial cameras. Their primary purpose is to reduce the effects of haze, both manmade and natural. Manmade haze will vary, depending on prevailing winds and other meteorological conditions. You will have to use your own particular experience to determine exactly how to handle the problem. It also is a major factor in aircraft navigation and can, under certain conditions, negate attempts to secure aerial photography on an otherwise cloudless day.

Many underdeveloped nations permit unrestricted agricultural burning during certain seasons. I found this to be true (15 years ago) over my wife's native Central America. The farmers would burn off the land prior to planting. Many March days were entirely cloudless, but the ground would be totally obscured even from an altitude of 1 km. Aerial photography, unless you were attempting to locate the offenders, would be practically useless under such conditions.

Certain areas of the world are also subject to natural haze in the atmosphere, which can degrade a photographic image.

The selection of filters is based solely on the job to be done. There are hundreds of kinds available. The publication *Kodak Filters for Scientific and Technical Use* will be of great value. One important rule to remember is: Never use any filter which might cause random or unknown distortions in the optical path if you plan to record accurate photogrammetric data.

CAMERA CALIBRATION INFORMATION

Before one can do any type of accurate work with an aerial camera, comprehensive knowledge of its calibration is mandatory. If you cannot secure the information from a reliable source or by means of measurements with your own laboratory equipment, you must consider the calibration an unknown factor and proceed accordingly.

You cannot tolerate unknown factors that might affect the accuracy or precision of your work. Therefore, do not attempt to make scientific deductions based on unknown or erroneous camera calibration information. You must know your camera thoroughly, including accurate knowledge of:

- radial lens distortion

- tangential lens distortion
- calibrated focal length
- transmission characteristics
- spectral characteristics
- resolution of lens
- flatness of focal plane with respect to optical axis
- accuracy of exposure at all shutter settings
- position of reseau markings and all other fiducial marks
- accuracy of any built-in accessories such as clocks, frame counters, altimeters, vacuum gages, data recorders, intervalometers, etc.

MULTISPECTRAL CAMERAS

If one wishes to record information from a discrete portion of the electromagnetic spectrum, a film highly sensitive to the desired portion of the spectrum is used in conjunction with a filter designed to eliminate unwanted information. If two or more such recordings are made simultaneously, the end result is multispectral photography. Multispectral cameras fall into two classifications:

(1) A single camera may be designed to secure multiple recordings on one or several film types. This may be accomplished by the use of two or more lenses, each with a specified filter, or through the use of a single lens and one or more beamsplitters consisting of special mirrors and/or filters to place the image at selected locations on the film. There may be a single roll of film in the magazine or several rolls having the same or different types of emulsion. A good example would be the Itek experimental camera shown in figure 8. It uses nine lenses to record simultaneously on three rolls of 70-mm film. There are several other cameras of this type available, using various techniques to achieve multispectral results.

(2) A gang of two or more cameras may be used to record with various lens-filter combinations simultaneously. Such an arrangement could employ several large-format aerial mapping cameras (figure 9) or, as I have seen, up to 12 of the 70-mm Hasselblad EL cameras (figure 10). In the Manned Spacecraft Center's Earth Resources Survey Program, multispectral photography has been successfully secured using the following camera systems:

FIGURE 8. Itek nine-lens experimental multispectral camera.

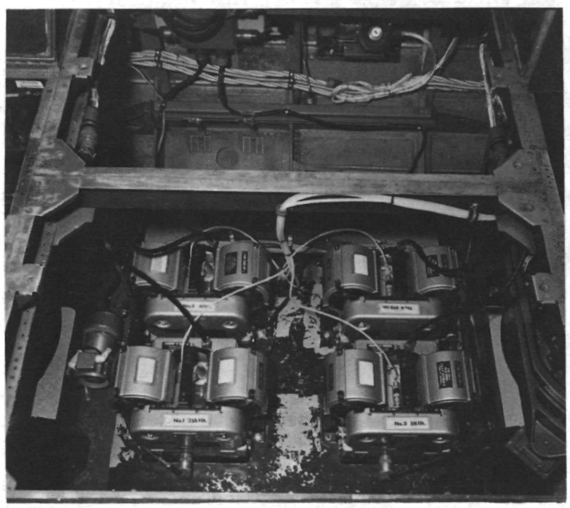

FIGURE 9. Four Chicago Aerial KS–62 75-mm multispectral cameras mounted in aircraft.

(a) Multiple 70-mm Hasselblad EL
(b) Itek nine-lens
(c) Multiple Wild RC–8 and Zeiss RMK systems
(d) Multiple Chicago Aerial KS–62 using 125-mm film

Apollo 9 used four Hasselblad EL cameras with various film-filter combinations to secure many multispectral space photographs.

In the Skylab Program, NASA will use a specially developed Itek multispectral system of high resolu-

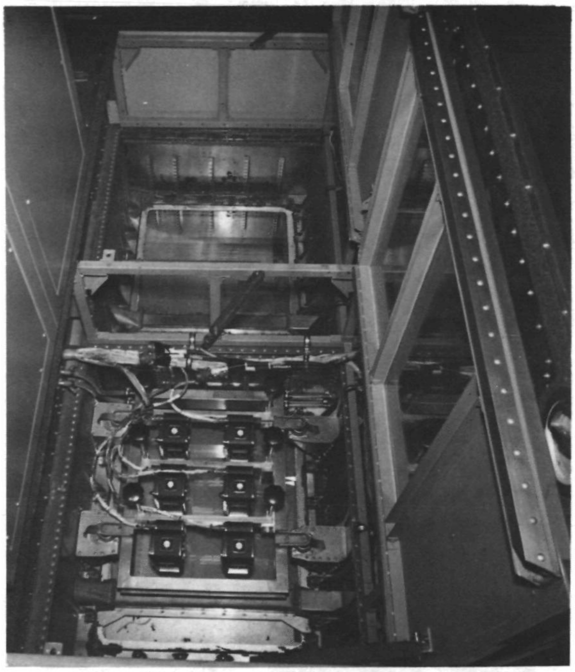

FIGURE 10. Six Hasselblad EL cameras for multispectral aerial photography.

tion and mapping precision, which takes six precisely matched photographs simultaneously.

If one chooses to develop a program using multispectral photography, a great many options can be exercised. Before an effective and practical program can be introduced, a great deal of experimentation is necessary. The use of a camera system like the Hasselblad EL has a number of advantages for experimentation. It is fairly inexpensive, and it is readily available in most parts of the world. Several can be fairly easily synchronized. Filters and lenses are not expensive, and they are easily interchanged. The 70-mm film magazines hold approximately 150 exposures each, depending on film thickness, and are quickly changed. This permits a great many experiments to be performed quite quickly at a minimal cost. It should also be noted that camera servicing facilities are worldwide.

You may, of course wish to consider other systems of a simpler or a more complex nature. The important thing is that your geoscientists and photographic scientists become fully aware of both the unique advantages and the limitations of multispectral photography.

FILMS FOR AERIAL CAMERAS

Most of the world's leading film manufacturers produce films especially created for aerial survey photography. At the Manned Spacecraft Center, practically all films used in the Earth Resources Survey Program are manufactured by the Eastman Kodak Company. Although NASA has many good reasons for this choice of manufacturer, each user must make his own decisions based on his particular situation and other factors outlined in this paper.

In theory, almost any film could be used for airborne photography. As a practical matter, however, films not specially designed for aerial photography may yield undesirable and erratic results and therefore should not be considered.

Aerial films are usually formulated to be relatively insensitive to the blue portion of the electromagnetic spectrum and slightly more sensitive to the red portion. The reason for this is that atmospheric haze—both natural and manmade—is usually blue. The film is thus relatively insensitive to its major problem, haze. Aerial films can be purchased in several thicknesses, in many widths and lengths, and on several types of base material. For geometrically accurate work, films on a polyester material are best. They exhibit very little residual shrinkage or expansion due to handling in the camera and processing. In fact, polyester or equivalent films have image dimensional stability approaching that of glass plates. They are desirable but not necessary if your goal is not precise measurements.

Aerial films are manufactured with many levels of sensitivity to various intensities of light. This is usually referred to as the speed of a film. Fast films, being very sensitive to light, are usually used where the subject is poorly illuminated or when very short exposure times are necessary. Slow films are usually preferred for well illuminated subjects when highest resolution is a requirement. The camera is usually the limiting factor, and films are selected on the basis of subject illumination and camera capabilities.

Aerial films have varied contrast capabilities. A high-contrast film is advantageous when a subject is of low contrast, and vice versa. Low contrast is usually produced by either a hazy atmospheric condition, a very high altitude, or a very homogeneous subject. Conversely, a low-contrast film should give

better results in low-altitude photography of a subject with high contrast. Many users prefer to manipulate contrast in the processing laboratory. Experience is the best guide to which technique will produce the best results in your own situation.

A good starting point would be with a fine-grain, medium-speed, polyester-base film such as Kodak Plus-X Aerographic Type 2402. For work in the infrared portion of the spectrum (to reduce haze effects, locate water or wet ground, or conduct forest surveys) and for multispectral photography, a film such as Kodak Infrared Aerographic Type 2424 should be considered.

When one reaches such a degree of sophistication in aerial photography that he feels ready to undertake color aerial photography, an entirely new dimension opens up. But it presents many problems. Probably the major decision will be whether to use color positive or color negative film. Both are readily available, and both have certain advantages as well as disadvantages (figures 11 and 12). One must consider the cost of the original material against its utility value, as well as the cost of reproduction.

My own experience indicates that you should consider color positive (i.e., color reversal materials) until both the photographic laboratory and user-geoscientists have developed the required skills of the trade. Color positive or color reversal materials have trade names that usually end in "chrome", such as Kodachrome, Ektachrome, Agfachrome, Anscochrome, and Fujichrome. The original film,

FIGURE 11. Aerial color photo (negative) of San Jacinto State Park, Texas (difficult to interpret).

FIGURE 12. Color positive of photo shown in figure 11 (much more easily interpreted).

when processed properly, yields a true and correct color viewing positive. The laboratory technician can use the original as a guide for his reproductions, and the geoscientist has a true spectral reproduction of the original scene.

Color negative films can be useless for interpretation (except for a few very skilled individuals), but they are somewhat easier to reproduce (that is, once the laboratory is skilled enough to insure true reproduction of the original scene). These films have trade names which usually end in "color", such as Kodacolor, Anscocolor, Agfacolor, etc. Eastman Kodak makes a large variety of excellent color positive and color negative aerial films. GAF Corporation and Agfa also make aerial color films which are in worldwide use.

For specialized work, you should be aware of such films as Kodak Aerochrome Infrared Type 2443, a film of especially great value in agricultural and geologic studies. Also, GAF has produced a two-color Anscochrome which is used in specialized oceanographic survey work. The user should survey the entire market and know the characteristics of all available films.

You will find that color films, like black-and-white films, require considerable experimentation before one is selected. Your research program will be a continuing one. Your photographic scientists will be required to test all the new and improved films being manufactured and the final selection must be based on whichever film best accomplishes your specific tasks.

SELECTION OF FILMS

Many factors must be considered before an aerial film is selected. These factors include:

(1) *Intended use of end product*

(a) Prior to selecting a specific film, the user must survey the technical literature of the various manufacturers to determine which film will best do the intended job. Of great importance is the film's sensitivity to light in the selected spectral region. In a film of wide spectral latitude, this is commonly called film speed and is measured in units of DIN or ASA. Speed is particularly important when low-transmission filters are to be introduced into the optical path.

(b) The granularity of the film must be considered. It usually bears a direct relationship to film speed. Slower or insensitive films are usually very fine grained. Fast, very sensitive films are usually coarse grained. There is little to be gained by using very fine-grained, highly resolving films unless your lens system is capable of producing a high-resolution image. As an example, it would be useless to have a film capable of recording 250 line pairs per millimeter. You would be making a great sacrifice in film speed with no possible gain in information.

(c) The physical properties of the film are another consideration. The film base material is of major importance. If you are considering making precise photogrammetric measurements, polyester-base films are highly recommended. It is also important to consider film thickness to insure proper passage through the camera system as well as the processing system.

(2) *Technical competence of the manufacturer.* This factor is of the greatest importance to your aerial surveys and will have a most profound effect upon your photographic results and the ultimate value of your programs. Remembering that your own specialized situations and experience will be your major guides, the following questions must be carefully considered:

(a) Do the available products meet your requirements?

(b) Does the manufacturer furnish detailed information on the physical and sensitometric properties of the film?

(c) Do your own studies and evaluations indicate that his information is reliable?

(d) Does he have specialized technicians and/or photographic scientists available to assist you with special problems and requirements?

(e) Do you find that a specific product yields essentially the same test results from one emulsion coating to the next?

(f) Will he help you analyze your water supply and chemicals and furnish recommendations based on his findings?

(g) Does he ship his product from his place of manufacture to your delivery point under conditions which will not cause degradation of sensitometric properties? Some films are exceptionally critical. Your Customs Office facilities must also be considered, if you import the film.

(h) Does he have a competent research staff which can help you?

(i) Is he easily accessible by cable, telephone, or letter? And does he respond to communications promptly?

(3) *Product availability.* There are a few manufacturers who advertise a wide variety of film products. Your problem may be in securing them. You should consider a manufacturer who keeps sufficient stock levels at strategic locations so that you can secure film in a reasonable time period. Some will manufacture a film only after sufficient orders are received to justify a profitable sale. In such cases your source is unreliable, particularly if you have a seasonal application. In some cases a manufacturer will prepare a very specialized film if you are willing to order a sufficient quantity. An example is Eastman Kodak S.O. (special order) films.

(4) *Level of laboratory competence.* You should secure testing samples of various films before you undertake any large-scale project. Your photographic scientists should conduct a series of studies to determine the sensitometric characteristics of each emulsion. Test films exposed in aircraft should then be processed in your laboratory. Processing should meet preestablished standards and goals. You should not consider using any film which cannot be processed and reproduced (if required) to meet the standards of your photographic scientists or user-geoscientists. If you do not secure reliable and repeatable results, you will find that you are furnishing your geoscientists with erroneous

materials, and hence erroneous deductions and conclusions will result.

(5) *Film cost.* There is one consideration in product selection which is valid only when all those that I have cited are absolutely equal, and that is the cost of the film. You will quickly discover that the cost of film is a very small portion of the cost of your program. Savings on the cost of a product which may be inferior can place your program efforts and results in serious jeopardy.

PREPROCESSING QUALITY CONTROL PROCEDURES

To create a photographic image of known properties with highly reliable information, the user cannot tolerate any break in the continuity of information about his aerial film. He must have a complete history of the environmental conditions to which the film has been exposed, from the moment the emulsion is coated through storage, shipment, and completion of processing. This consideration must include the environmental conditions in both the aircraft and the laboratory. The exact sensitometric characteristics of the emulsion are a function of the total environment to which it has been exposed as well as its manufacturing formulations. Each manufacturer will furnish a report as to the sensitometric and physical characteristics of each type of film to be manufactured. Experience has told us that this is generally an excellent guideline. It should not be considered absolute fact, however.

The manufacturer will usually use very exacting techniques and highly competent personnel in formulating an emulsion. It is then coated to the film base and cut into rolls. Each emulsion formulation is called a batch. For some usually unexplainable reason, each batch differs slightly from other batches of the same emulsion made under the same conditions. Hence, the user, planning to make exacting geoscientific measurements must conduct his own analyses of all films as soon as they are received. It therefore makes good sense to insist that all film in a specific shipment come from the same batch (that is, with the same emulsion number).

The user has a responsibility here also. He should secure his film in as large an order as practical and have adequate storage space with temperatures no higher that 15 °C and preferably 0 °C or below. Film will not greatly change in sensitometric response if stored frozen, even for long periods.

Upon receipt of a film shipment, the photographic scientist should make his own comprehensive analysis of its sensitometric characteristics. In some cases, he may call for storage of the film under certain temperature conditions for a specific time to shift its spectral characteristics to a desired condition. In other cases, he may require a change in exposure or a specific filter to be used. He may also modify the film processing techniques. In certain cases, he may reject the shipment as unusable for its intended purpose.

To accomplish such detailed investigations of aerial films, the photographic scientist must have accurate equipment. An accurate sensitometer, a controlled processing capability, and a densitometer are necessities. Other equipment can make his investigations even more detailed and accurate. The sensitometer permits him to expose emulsion samples to exact amounts of light in contact with an accurately calibrated density scale. The controlled processing usually includes accurately formulated chemicals, precise temperature regulation, precision timing, and accurate and thorough chemical agitation. The densitometer permits the scientist to determine accurately the response characteristics of the film.

When the film is removed from storage prior to an aerial photographic mission, the photographic scientist repeats his tests to insure that the film has not changed in sensitivity. He also places an exposed sensitometric density scale on the loading end of the film (occasionally both leading and trailing ends). During an actual photographic mission, the film should be subjected to a normal environment. Cold air in a high-flying aircraft will not degrade the film, but temperatures in excess of 35 °C can cause serious problems (depending on the type of film, the duration of the condition, and the humidity).

Upon return of the film to the laboratory, the photographic scientist will place another sensitometric density scale on the film. He may also remove an unexposed portion of the film, place a sensitometric density scale on it, process it, and determine if there has been any image degradation during the mission. Also he should simultaneously expose a sensitometric density scale on a laboratory controlled film from the same emulsion batch.

The resulting information will permit him either to alter the processing technique or to detect a change in the sensitometric characteristics significant enough to be brought to the attention of the geoscientists using the film.

The important message here is that quality control is mandatory for a quality product. These procedures will vary with each user and will evolve as your program develops. No matter how rudimentary or sophisticated your surveys are, you should always insist on the most comprehensive quality control practices commensurate with the desired end product.

PHOTOGRAPHIC PROCESSING OF AERIAL FILMS

The third link in the chain of aerial photography is the all-important work within the photographic laboratory. In this phase of workmanship, quality control and a comprehensive knowledge of photographic science are an absolute necessity. Poor work, incomplete records, or substandard quality control can totally negate the very expensive aircraft operations which are performed to secure a precision photographic record.

PROCESSING LABORATORY EQUIPMENT

Photographic laboratories vary in sophistication from a wooden sink in a darkroom to multimillion-dollar complexes designed to enhance the state of the art. I have seen aerial photographs made with the finest Zeiss or Wild aerial cameras in multimillion-dollar jet aircraft, then processed in a wooden sink using a hand rewind system, chemicals purchased in a hobby shop, and water from a city tap. The resulting film looked good, but no one would ever know if it really was.

Such a simple approach to aerial film processing usually does yield good pictorial quality; in reproduction, the technician can redeem many of his original mistakes. But much may be lost forever. If your goal is good pictorial quality, such a simple solution may be adequate for your needs. However, do not attempt to make any specialized scientific deductions from film processed in this manner.

If one is willing to invest great financial resources in aircraft and/or high-quality aerial cameras, one should never overlook the fact that the photographic laboratory must be equipped to make full use of the information secured. Here, too, one should commence operations with fairly simple equipment and techniques so that the photographic scientists and technicians can fully comprehend the science as well as the art.

The tank processor for rolls of aerial films has been in use for over 40 years. The Zeiss Model FE–120 (figure 13) does an excellent job.

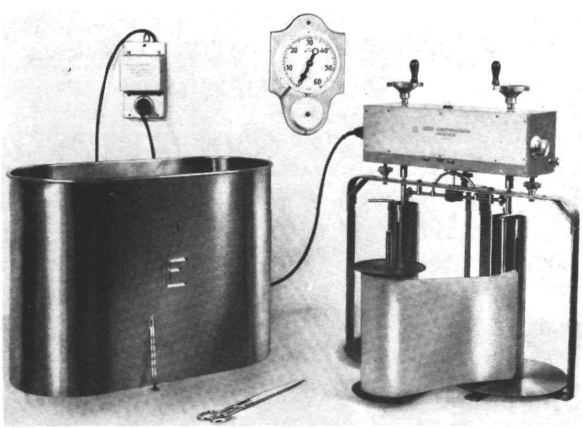

FIGURE 13. Zeiss FE–120 rewind aerial film processor (courtesy Carl Zeiss Co.).

Basically, the tank processor permits a technician to immerse roll film into tanks of chemicals, and an electric motor winds the film back and forth from spool to spool. A good tank arrangement for black-and-white film is:

(1) wetting agent
(2) developer
(3) stop bath
(4) fixation
(5) wash

Steps 1 and 3 are not always necessary.

For color films the process is very complex and time-consuming, and results can be both mediocre and erratic. It is a 16-step process which requires exacting adherence to procedures and is too complex to discuss in this paper. (See American Society of Photogrammetry *Manual of Color Aerial Photography.*) It should be noted that a dedicated technician can do high-quality work with a rewind system. He can introduce a number of excellent quality control procedures which greatly improve film quality and repeatability. These include:

(1) *Temperature control.* This can be accom-

plished by bringing the chemicals to temperature equilibrium with the darkroom. That would be a cool 20 °C in most cases. Another method entails the use of temperature-controlled mixing valves with sinks serving as a temperature-controlled water jacket to achieve equilibrium. A thermal heat exchanger, such as the Pako Corporation Pakotemp, could be used to recirculate and temper this water jacket.

(2) *Quality control of chemicals.* The technician can insure that each batch of chemicals is prepared with extreme care. This includes dilution at proper rates and temperatures, complete blending at proper temperature, and making sure the correct total quantity is made. In addition, he can conduct a number of tests on the resulting chemicals, including specific gravity, pH, and even a qualitative and quantitative analysis.

(3) *Water purity.* All water lines should contain efficient filters which are periodically changed. A complete laboratory analysis of the water should be conducted periodically.

(4) *Chemical replenishment.* A skilled technician can alter the chemical depletion characteristics of the rewind system by trial-and-error experimentation. A replenisher chemical must be added to each tank at a specific rate and time.

(5) *Proper film drying.* Film should be dried at the proper temperature and humidity in a room which is free of all airborne particulate matter. An air filtration system should be functioning for a number of hours prior to and during the drying operation.

(6) *Sensitometric controls.* The technician can preexpose a sensitometric scale on film which is processed with each roll of aerial film. A densitometer can then be used to record the final process and provide the information to the geoscientist.

(7) *Accurate recordkeeping.* A competent technician will keep comprehensive records of all information for every roll of aerial film processed.

(8) *Time-gamma studies.* The technician can conduct a series of tests which show the effects of various parameters on the sensitometric characteristics of processed film. He can vary development time, temperature, chemicals, replenishment rates, etc. These tests, in conjunction with his accurate recordkeeping will permit him to process and reproduce aerial photography with the wide variety of results which may be required by the geoscientist.

The automatic aerial film processor was introduced in the late 1940's. Early models were generally not too effective. Problems were numerous and results were generally no better than those achieved by a competent technician. Equipment costs were great when evaluated against results.

During the 1950's many improvements were made, and in the early 1960's an economically feasible automatic film processor came on the market (namely the Eastman Kodak Versamat, model M–11). This roller transport aerial film processor proved exceptionally reliable, extremely versatile, and economically practical. Using this equipment, a technician who could process two rolls a day could now process 20 or more to far more exacting specifications. This increase in production quickly offset the cost of the equipment.

The versatility of the Kodak Versamat is outstanding. The technician has a great range of chemicals available. He can quickly introduce and exactly hold a large range of temperatures. He can select from a wide range of processing times. Chemical replenishment is accurate and simple. In addition, film is properly dried in dust-free air, and sensitometric repeatability is excellent.

You may wish to investigate the photographic market and evaluate a number of automatic aerial film processors, but in my opinion the Kodak Versamat should be the standard that the others are evaluated against. At the present time, several Versamats are in constant use within the Earth Resources Survey Program at the Manned Spacecraft Center. For your particular application, however, you may find that other automatic film processors are better suited.

Following the development of the Kodak Versamat, the next logical step was to produce a similar device for aerial color films. The Kodak roller transport aerial color film processor, generally called the Color Versamat, was introduced in 1965. It is this device that made aerial color films totally utilitarian and economically feasible. It permits those who use color films in their geoscientific studies to secure accurate and repeatable results, and this equipment should be given serious consideration if color or color infrared photography is contemplated. These machines can process color

positive or color negative aerial films with equal facility.

No matter which type of automatic equipment is utilized, the importance of high-standard quality control procedures cannot be overemphasized.

CONCLUSION

This paper has stressed the importance of having a complete knowledge of your films, cameras, processing, and reproduction equipment. This knowledge, coupled with comprehensive, well documented quality control techniques, will produce information of immense value and of great significance to your country and its people.

If these recommendations go unheeded, the very opposite may result. Consider, for example, the improper use of a specialized film designed to detect a virus-type infection in a nation with a one-crop economy. The source and spread of the virus may go undetected until the entire nation is infected, and catastrophic economic conditions as well as great human suffering can result.

This hypothetical situation, of course, is an extreme case. I have asked my wife what she would think if her beloved Honduras lost an entire crop of bananas, rice, beans, or coffee to a virus or insect plague. Her reaction was one of horror and dismay for our friends and relatives in her native land.

The information presented in this tutorial paper is based on knowledge gained through the mistakes and successes of a quarter century in the profession. My first attempt at aerial remote sensing began with a $20 camera and a small piece of infrared film in a rented Piper Cub, trying to locate a geologic fault zone hidden under glacial debris since before man occupied North America. It was an unqualified success and enabled me to complete a university thesis. Recent assignments have dealt with highly sophisticated cameras being used by our astronauts to record geologic information on the far side of the moon.

The most important point I have tried to establish here is that only you and your scientists can determine the best system to accomplish your specific requirements. It was, I think, best said 2500 years ago by one of the most important human beings ever to inhabit our Earth:

"Believe nothing merely because you have been told it, or because it is traditional, or because you have imagined it. But whatsoever after due examination you find to be conducive to the good and to the welfare of all being—that doctrine believe and cling to it, and take it as your guide." The author was Gautama Buddha.

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Earth Observation Sensors

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Scanning spectroradiometers are commonly used in Earth observations from space because they can obtain images of radiation backscattered by or emitted from the Earth's surface at spectral intervals ranging from the ultraviolet to radio waves. Sensor design depends on the required sensitivity, spectral resolution, spatial resolution, and geographic coverage. These requirements vary with mission objectives. In general, sensors for such exploratory missions as Skylab and aircraft surveys are governed by the first two requirements, while sensors on global survey missions such as ERTS follow more closely the latter two. Depending on the application, compromises are usually necessitated by limitations of the sensors in meeting these design requirements. Examples of such compromises are discussed and the factors leading to the design of the multispectral scanner (MSS) on ERTS and similar sensors on future spacecraft are described.

Remote sensing techniques for observing both the atmosphere and the Earth's surface are based on measurements of the spectral and spatial variance, with time and over large areas, of the intensity of electromagnetic radiation which is either reflected or emitted by the Earth and its atmosphere. Methods and instruments for observing the Earth from space, therefore, are analogous to those used by astronomers, who derive information on the temperature, composition, and structure of planets and stars from observations of the spectral character and patterns of radiation received from these objects.

Indeed, the sensors used for Earth observations from space (namely, spectral cameras, spectroradiometers, and spectrometers) are the same as those used in astronomy except that they are pointed toward the Earth. For this reason, Earth observation from space has sometimes been referred to, very appropriately, as "upside-down astronomy."

While the observational methods and instruments are very similar in the two disciplines, the purposes of the observations are quite different. In astronomy, they are the only means available for exploring the unknown. In Earth observations, on the other hand, the observations are employed to find the most effective and economic means to monitor and survey variations of known environmental parameters on a global scale.

Exploratory studies are being conducted to identify the radiative characteristics of objects such as snow, ice, minerals, plants, water, suspended organisms, and pollutants. For this purpose, sensors are designed to make precision measurements in many narrow and discrete bands of the solar spectrum (from ultraviolet to the near infrared) and the terrestrial spectrum (from the near infrared to radio waves), shown in figure 1. The choice of spectral bands for the ERTS program has evolved from knowledge obtained in previous exploratory aircraft and laboratory experiments. The five specific bands chosen for ERTS resulted from the following considerations:

(1) Very little solar radiation is reflected by vegetation at wavelengths shorter than 0.7 μm, while terrain not covered by vegetation may show strong contrasts in this portion of the spectrum, depending on composition and structure.

(2) There is strong reflection by vegetation between 0.7 and 0.9 μm, varying greatly with the type and health of the plant life.

(3) Reflected solar radiation from the Earth's surface at about 1 μm depends strongly on the

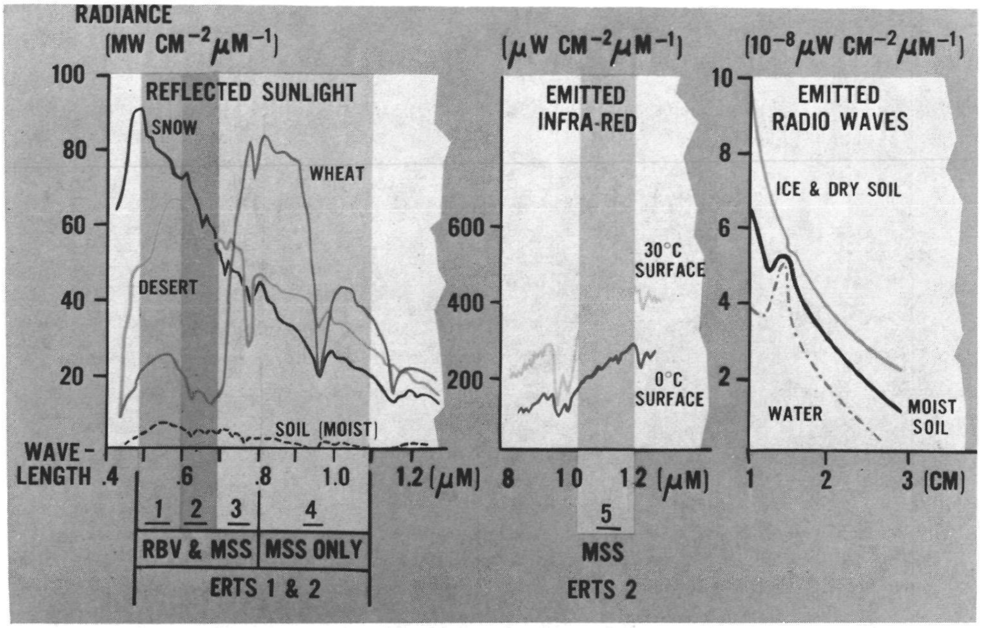

FIGURE 1. Typical spectra of solar radiation reflected from the Earth (left), of emitted terrestrial radiation in the 8-to-12-μm spectral band (center), and of emitted terrestrial microwave radiation (right). Sharp spectral features in reflection spectra (left) and in microwave emission spectra (right) are primarily due to atmospheric water vapor. Absorption features near 9.6 μm in infrared emission spectra (center) are due to atmospheric ozone. Reflection spectra are from aircraft observations, infrared emission spectra were observed with the Nimbus 3 satellite, and radio spectra are from computations and aircraft observations.

amount of water on the surface, and reflectance decreases rapidly with increasing moisture.

(4) Radiation measured at 11 μm varies directly with the temperature of the surface. Future instruments on Earth observation satellites will make use of the characteristic difference in the microwave emission of ice and water to map the distribution of polar sea ice.

The four factors that generally determine the design of sensors for Earth observations are sensitivity (signal-to-noise ratio), spectral resolution, spatial resolution, and areal coverage. Depending on the specific objective, one of these usually dominates the design at the expense of the others. For example, since areal coverage is relatively unimportant for exploratory observations, they are usually made from aircraft, thus simplifying optical and mechanical design because the requirements for spatial resolution and scanning are much less severe on aircraft than for spaceborne instruments.

Most of the sensors in the Earth Resources Experiment Package (EREP) aboard Skylab are also used for exploratory purposes, with emphasis on identifying spectral signatures and delineating highly selective features. These instruments usually have very high spectral resolution, excellent sensitivity, and spatial resolutions of 50 to 100 meters at optical wavelengths, but they make measurements relatively infrequently over only a small number of selected sites. More frequent observations with greater areal coverage would be inadvisable with such instruments for two reasons:

(1) Combining high spectral and spatial resolution with wide and frequent coverage would make the sensors unnecessarily complex and expensive.

(2) The amount of information gathered in this case would be so great as to defy analysis by even the most sophisticated automatic methods available.

For periodic and global surveys and for monitoring from space in broad predetermined wavelength bands, it is necessary to observe large areas routinely and frequently. Although spectral resolution and sensitivity are reduced to some extent, spatial resolution must be maintained. To do this while meeting the areal-coverage and frequency-of-observation requirements calls for very sophisticated

and expensive sensor systems, such as those to be flown on ERTS. Areal coverage is achieved either by imaging an entire radiation scene instantaneously onto a photosensitive surface (such as film or the photocathode of a TV tube) or by scanning the beam of a radiometer across the Earth's surface at right angles to the motion of the observation platform, so that an array of consecutive scan lines forms an image strip along the path of the vehicle. Because films and TV tubes have a much more limited spectral response, scanning radiometers are always used for observations at wavelengths longer than 0.8 μm.

The sensors aboard the ERTS will cover a strip of Earth surface 180 km wide, directly under the orbital track of the spacecraft. Because of the orbit chosen, longitudinally adjacent strips will be observed at the same local time on consecutive days so that a complete low-latitude zone will be covered in 18 days (figure 2) while higher latitude zones

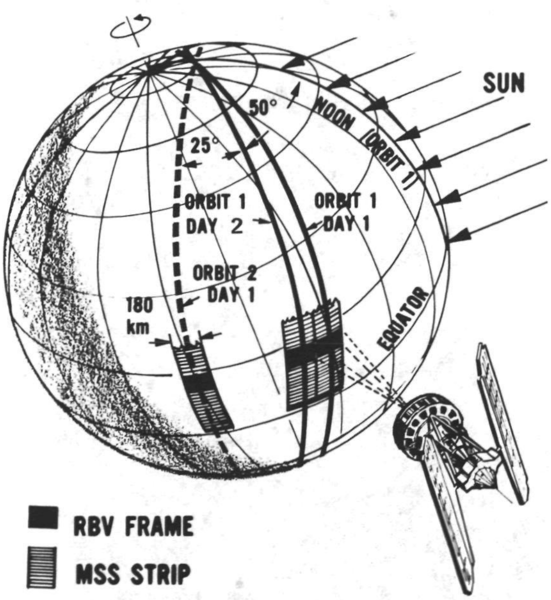

FIGURE 2. Coverage by ERTS return-beam vidicon (RBV) camera and multispectral scanner (MSS) for two consecutive orbits on the same day and for the same orbit on two consecutive days. Coverage of 180-km-wide strips on consecutive days will be contiguous at the equator, so that orbit 1 on day 18 will be adjacent on the east to orbit 2 of day 1. The relation of each orbit to the Sun angle is constant; it is shown properly for orbit 1 of day 2 in this figure. The RBV and MSS will view congruent areas, but RBV coverage will be a series of 180-by-180-km frames while MSS coverage will be obtained by scanning sequentially across the 180-km-wide strip.

will be covered in shorter periods. No coverage will be obtained poleward of 80°. By use of an onboard tape recorder, 144 images covering an area of 180 by 180 km each can be transmitted to the ground in each spectral band during a 24-hour period. This coverage requires a minimum satellite altitude of about 800 km, placing a very severe burden on the sensor design to achieve a spatial resolution on the order of 50 to 100 meters.

These resolution and coverage requirements led to the design of a multispectral scanner (MSS) for ERTS consisting of a 23-cm-aperture telescope which scans an instantaneous field of view of about 88 microradians, sweeping across the satellite track to about 6° on either side of the nadir at a rate of about 13 times per second (figure 3). This sensor will cover five broad spectral bands centered at 0.55, 0.65, 0.75, 0.95, and 11.0 μm. The 11-μm channel will be omitted from the first ERTS mission. In contrast to the exploratory observations from aircraft and Skylab, only a small number of spectral bands can be accommodated on ERTS, partly because it is necessary to limit the data acquired and transmitted by the satellite to manageable quantities. The five spectral channels alone result in almost 10^{10} measurements of spectral radiance to be transmitted to the ground in each 24-hour period.

Thus, sensor systems for Earth resources surveys from space are developed in a complementary fashion. Laboratory and aircraft observations with spectrometer-type sensors are conducted over small but carefully selected areas. Space observations for global surveys covering large areas at frequent intervals call for the design of more complex, rapidly scanning radiometers with a modest number of channels, high spatial resolution, and a capability for contiguous mapping. Looking beyond ERTS, we are planning to design scanning radiometers which will image the emitted terrestrial radiation in one or another band of the microwave spectrum for the purpose of mapping sea ice (figure 4). Eventually there might be radars to map the ocean surface and subsurface terrain features. These and other such advanced sensors are being developed out of present-day aircraft and Skylab missions and may be flown on future Earth observation satellites.

By far the greatest challenge to successful Earth resources surveys in the future will be the inter-

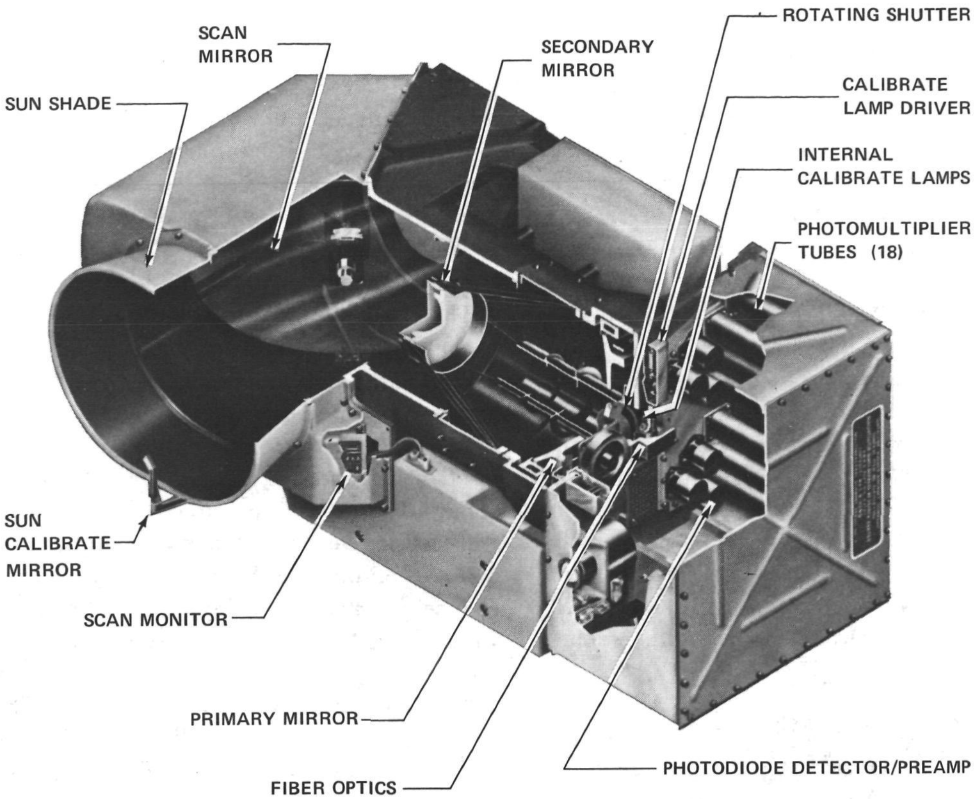

FIGURE 3. Cutaway view of preflight model of multispectral scanner for ERTS.

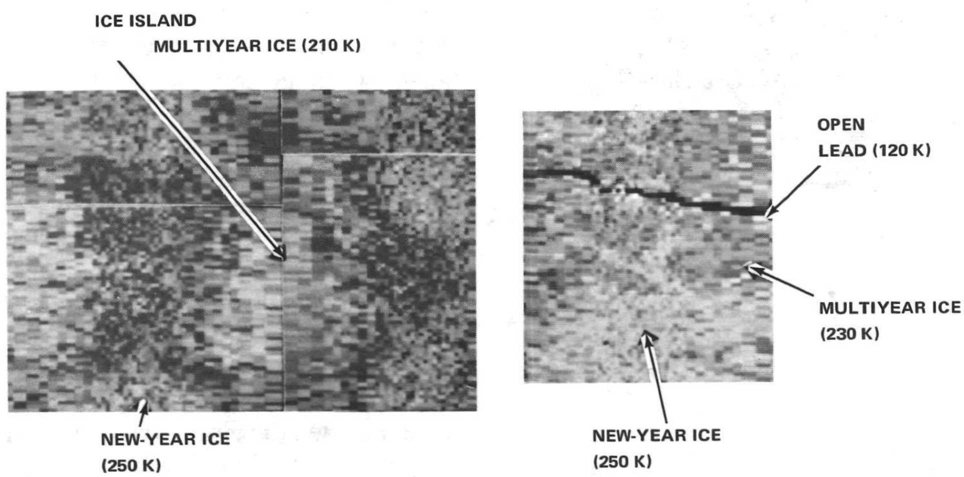

FIGURE 4. Images of emitted radiation at 1.55-cm wavelength obtained from aircraft over Arctic sea ice. Strongest emission (highest equivalent temperatures, represented by yellow and green) is from youngest ice, somewhat weaker emission (lower temperatures, blue and purple) is from older ice, and weakest emission (lowest temperatures, black) is from open water.

pretation and utilization of observations to be made from space. Technologists now have means to reduce the inundating stream of observations arriving from sensors to images of radiation intensities corresponding to vegetation cover, surface composition, or soil moisture. Physical scientists will have to supply models, either empirically or computationally, to derive from these observations an understanding of environmental factors such as the timber yields and crop cycles of particular regions, the dynamics of pollutants, the water resources of certain regions, the mineral composition of the Earth's surface, and many others. Only a very few such models, most of them very primitive, are being developed at this time.

The ultimate utilization of spaceborne Earth observations rests with the managers who will make decisions for the conservation and proper management of Earth resources. These management decisions properly should be derived from processes and phenomena which will be discovered, and described by models based on the observations themselves. Such decisions and controls could, for example, involve regulation of pollution, use of water resources, mining, or lumbering. While the first decade of the space age was marked by developments in spacecraft and sensor technology, the next decade will probably be devoted to two new phases: (1) modeling of the physical processes involving resource parameters and (2) learning how to make resource management decisions based on observations which we would not have dreamed of 10 years ago and which are difficult to conceive of, even today.

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Radar and Microwave Radiometry

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Microwave sensors are unique in that they can be scheduled for use almost without regard to weather or time of day. Both radar and microwave radiometers receive signals strongly affected by roughness and by moisture content of soil and vegetation. Microwaves penetrate vegetation and, to a limited extent, soil; but most response is from the upper layers of vegetation or the upper few centimeters of soil. Radiometers have relatively poor resolution in space, but radars may obtain resolutions of a few meters to tens of meters even from very long distances. The most important microwave sensor for Earth observations is the sidelooking radar, because its output is most like a photograph. The good resolution of such radars is maintained for long distances by the synthetic aperture technique. Good rendition of gray scales requires use of averaging techniques such as panchromatic illumination.

Radar has been used in Darien Province, Panama, to prepare a topographic map, a geologic map, and a geomorphic map. Radar has been used for geologic work, and its potential has been indicated for mapping crops and natural vegetation, land use, soil moisture, and snow. Both radar scatterometers and microwave radiometers appear to respond to wind speed on the ocean. Examples are indicated for several of these uses of microwave sensors.

Radar is a unique type of sensor. With a radar sensor the same picture may be made at any time of day or night. Microwave sensors are also unique in that microwaves penetrate clouds. Depending on the wavelength and the precipitation rate, microwave sensors may also see through rain or snow. Since much of the world is covered with clouds at any time, the ability of the microwave sensors to see through clouds makes them extremely important to Earth resources surveying.

The side-looking airborne radar (SLAR) is the most useful microwave sensor over land. By January 1971, SLAR applications had been proven in the fields of agriculture, natural vegetation mapping, geology, hydrology, cartography, geomorphology, geography, and oceanography. Specific applications within these fields have been considered by other speakers and are documented in the literature.

Nonimaging radar scatterometers have been shown to be useful for measuring oceanic winds and sea ice. Their application in measuring snow and soil moisture has been postulated. Their first use was for measuring backscatter to establish radar design parameters, and they continue to be valuable for this purpose.

Microwave radiometers have been shown to be sensitive to ocean temperature at some wavelengths and to ocean roughness at other wavelengths. They have been used to define atmospheric profiles, and experiments have been conducted to demonstrate their value in measuring snow, ice, and soil moisture. Their application to measuring atmospheric attenuation in the presence of clouds and rain has been proven.

The microwave radiometer and the nonimaging scatterometer are both limited to a relatively small number of applications, compared with the SLAR, by their poor spatial resolution. Potentially, the SLAR can achieve resolutions from spacecraft comparable to those of photography, but the spacecraft microwave radiometer and nonimaging scatterome-

ter will always be restricted to resolutions of kilometers.

The following sections discuss what microwave sensors measure, the effects of the atmosphere on microwave sensors, radiometer and radar systems, examples of applications of radar, and examples of radar systems.

WHAT MICROWAVE SENSORS MEASURE

A camera, a microwave radiometer, and a radar all receive radiation from the same piece of ground, but originating in different places. The ground is illuminated for the camera by direct sunlight and by light scattered from both the sky and the clouds. The light reaching the camera is reflected or scattered from the surface. The microwave radiometer views radiation from a larger complex of sources: Thermal energy is emitted from the ground, part of it coming from the surface and part coming from points beneath the surface; signals scattered to the radiometer from the ground originate in the Sun, the Galaxy, the atmosphere, and clouds. The radiometer also receives direct emission from atmospheric gases and clouds.

The radar is much simpler; the only radiation it actually uses is energy provided by its transmitter and backscattered from the surface. The radar also receives the other signals observed by the microwave radiometer, but it discriminates against them.

Ground scatter is the most important source of radar signals and is important in determining both the scattered and emitted signals received by the radiometer. The factors controlling the ground scatter may be divided into two categories: properties of the radar or radiometer, and properties of the ground.

The experimenter or the engineer designing the microwave instrument may select a wavelength between about 1 millimeter and 1 meter. He may select the polarization (direction of the electric field) to be vertical or horizontal, or circular, rotating either of two ways. He may choose to observe by looking nearly straight down from the aircraft or by looking nearly horizontally. Furthermore, by selecting his flight path, he can have his sensor observe any particular area from different directions. The scatter that is observed also depends on the resolution used.

Besides these factors under the control of the designer, scattering from the ground is determined by properties of the ground itself. The roughness of the surface (to the scale of the wavelength) is probably the most important factor. Roughness and granularity in the subsurface to the depth penetrated by the signal are also important. The dielectric and loss properties of the surface and near subsurface are equally important. In fact, the scattering is a product of functions of roughness and of dielectric properties.

A perfectly smooth surface would reflect all incident rays in the specular direction. As shown in figure 1, a relatively smooth surface scatters

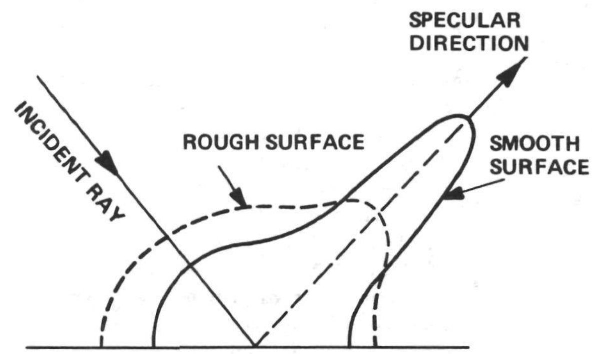


FIGURE 1. Intensity of scatter for oblique incident ray.

most radiation in the specular direction and near it, but also scatters a small amount in all other directions, including back toward the source. A rougher surface scatters more uniformly, although most surfaces are smooth enough so that scattering in the specular direction is somewhat greater than in any other. The radar signal contains only radiation scattered back along the incident ray, while the radiometer receives a composite of signals coming from different incident directions.

Figure 2 shows the variation in backscatter as a function of incident angle. This, of course, is important to the radar. For the smooth surface, the strongest backscatter signal comes from near vertical, because the vertical is the specular direction. For rougher surfaces, the vertical signal is still stronger than at other angles, but not so much stronger.

For microwavelengths, smooth surfaces are materials such as water, pavement, and bare soil. Even quite rough sea is smooth compared with most land

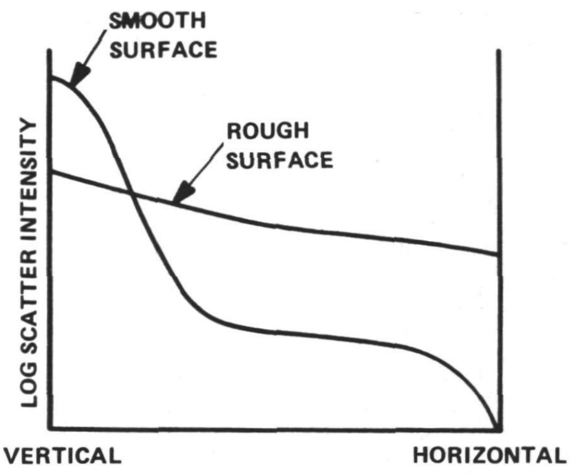


FIGURE 2. Backscatter vs incident angle.

surfaces. Rough surfaces include dense forest and dense crops, such as sugar beets. Less dense crops like wheat and grassland tend to be intermediate in smoothness. Dielectric properties, along with roughness, control wave scattering.

The most important factor determining the dielectric properties of natural materials is moisture content. Only a few solid natural materials have dielectric constants approaching 10, and most are less than 6 in the absence of moisture. Water, on the other hand, has a microwave dielectric constant in the range of 60 to 80.

When moisture is mixed the soil, or when moisture is present in plants, the dielectric constant increases rapidly with an increase in the percentage

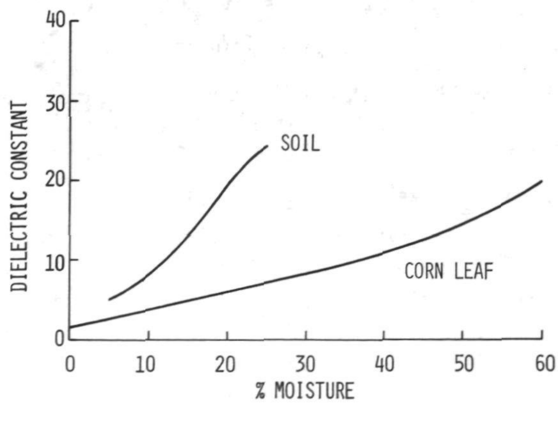


FIGURE 3. Dielectric constant of soil and corn leaf as a function of moisture content.

of moisture. Figure 3 shows this function for typical soil and plant matter.

Since much of the earth is covered with vegetation, the amount by which the microwave signal penetrates the vegetation is most important. Although some writers have stated that 1-cm-wavelength radar signals appeared to penetrate dense forests, this is not true. When a forest is dense, the radar return at 1 cm comes only from the treetops. At a longer wavelength, say 1 meter, a nearly vertical radar signal can penetrate the relatively small distance of dense leaves and reach the trunks of the trees and the ground. Even at this wavelength, however, a signal nearly parallel to the top of the forest does not penetrate all the way to the ground. For relatively short vegetation, as in a field of wheat, even a 1-cm signal, if it strikes nearly vertically, may penetrate through the vegetation to the soil. A nearly horizontal signal, however, receives most of its scattering from the wheat plant itself and not from the soil. At a longer wavelength (e.g., 1 m), penetration to the soil and even the subsoil is likely at any angle for short vegetation like wheat.

Penetration into the soil depends strongly upon the amount of moisture present and the wavelength. The radiometric and the radar signals come almost entirely from that region close to the surface where the incoming power is reduced by less than 85 percent. As shown in figure 4, different soils permit different amounts of penetration, but for any soil with very much moisture, penetration is not very deep even at a 1-meter wavelength.

The radiometer signal is dominated by emission from the ground if the waves experience little absorption in the atmosphere. The effective temperature is the product of the emissivity and the actual temperature of the ground. The total emissivity is one minus the total reflectivity and is equal to the relative absorption. Water near the surface increases reflectivity and consequently reduces emissivity. Hence, a dry surface has a relatively high emissivity.

The effective temperature of most land surfaces lies within a very small range of values. The relative backscatter, on the other hand, differs for different materials by factors of 10 or more. Thus, a microwave radiometer must be much more accurately calibrated than a radar to distinguish between different terrains.

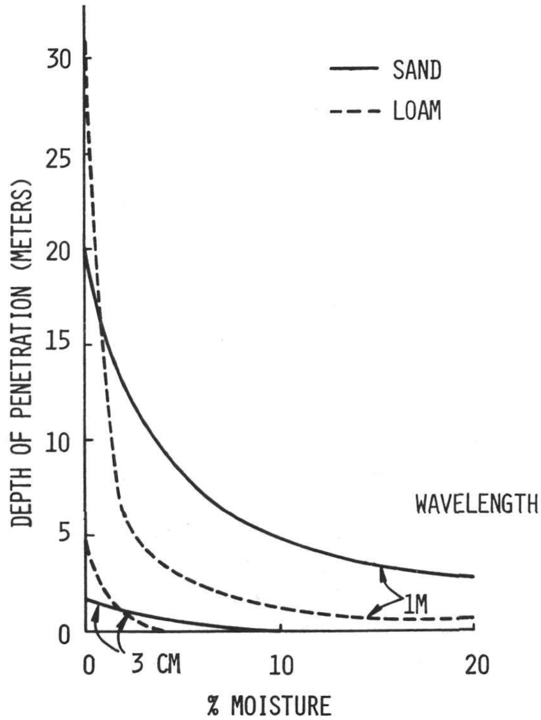


FIGURE 4. Soil penetration: depth of penetration where power reduced to 15% of surface power.

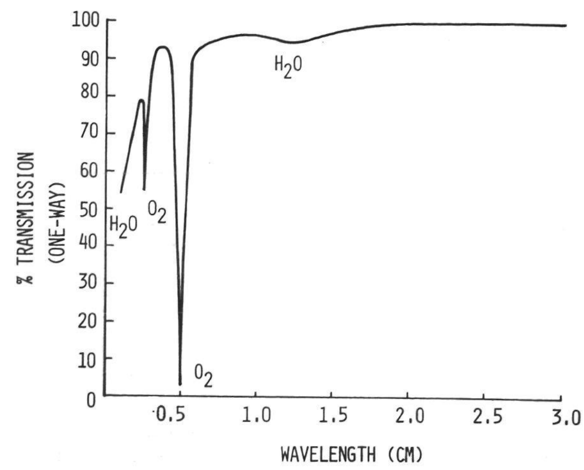


FIGURE 5. Effect of atmospheric gases (O_2 & H_2O) on radio transmission from space to ground.

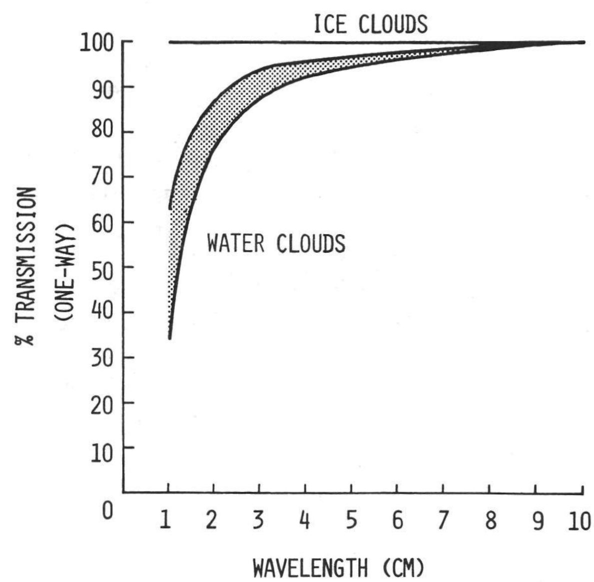


FIGURE 6. Effect of cloud on radio transmission from space to ground.

ATMOSPHERIC EFFECTS

Although microwave signals are affected less by the atmosphere than visible and infrared signals, they are reduced at certain wavelengths by atmospheric gases, clouds, and precipitation. Figure 5 shows the reduction due to atmospheric gases in transmission through the atmosphere at the zenith. The longest-wavelength absorption band is at 1.35 cm and is due to water vapor. This band shows very little effect here for vertical transmission, but it is very important for transmission along paths extending many kilometers through the lower atmosphere. Microwave radiometers can be used to determine atmospheric water vapor density by measuring at frequencies close to this absorption maximum. Most microwave equipment operates at wavelengths longer than 1.35 cm, but the maximum of transmission near 0.85 cm is also used for radar systems.

Cloud absorption of radio signals is strongly dependent on wavelength, as shown in figure 6. The attenuation is much greater for water droplets than for ice clouds. Although the transmission is reasonably good for most water clouds at realistic water densities and for a path through the atmosphere toward the zenith, transmission may be greatly reduced on paths passing through many kilometers of cloud if the wavelength is shorter than about 3 cm. The only atmospheric effect likely to reduce significantly the transmission of radar signals is precipitation. Figure 7 shows that heavy precipitation can have a great effect at wavelengths of 3 cm or

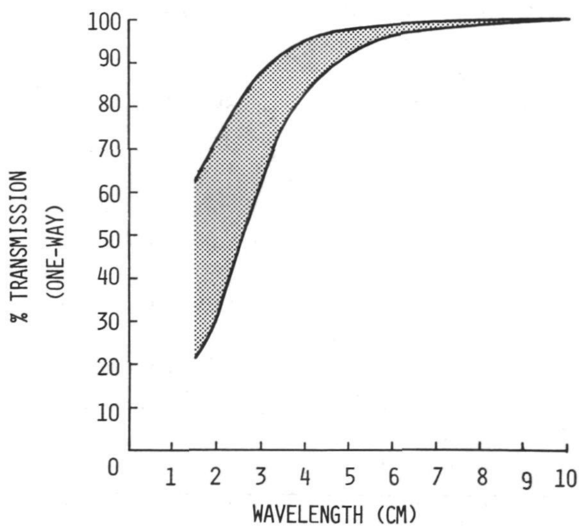


FIGURE 7. Effect of rain on radio transmission from space to ground.

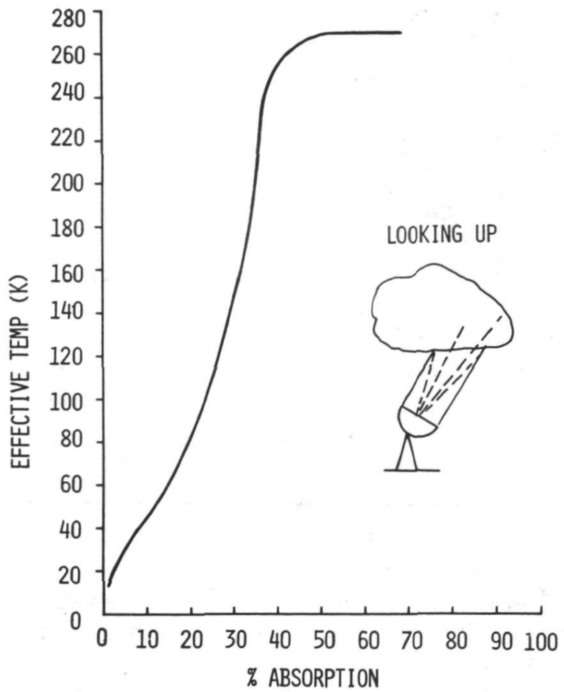


FIGURE 8. Microwave "brightness" of cloud at 16 GHz.

shorter. Light precipitation is seldom significant for a radar, although it may be very important for a radiometer.

Atmospheric absorption decreases the signal reaching a radiometer from the ground, but adds radiation from the cloud itself (figure 8). Even when transmission is as much as 75 percent, the measured effective brightness temperature of the ground may be significantly changed and the contrast reduced at the radiometer. If ground and cloud are at about the same temperature, the net observed temperature remains unchanged, but differences in ground temperature are masked by the cloud. If the brightness temperature of the surface is low, like that for water, even a small change in transmission between radiometer and the surface causes a large increase in the brightness temperature observed by the sensor. This effect is used in observing the water vapor content in the atmosphere, and it can also be used to study clouds and precipitation by appropriate choice of radiometric wavelength. Although atmospheric transmission for a radar may be reduced to less than half, the only effect on the output is a reduction in signal without a change in contrast. However, if the weakest signal should be reduced so that it cannot be distinguished from the noise of the receiver, the contrast will be changed.

Weather radar depends on backscattering from clouds and rain, but uses upward-pointed antennas. Normally the ground echo received by a radar with a downward-pointed antenna is much stronger than the rain echo, but for higher frequencies the rain echo may obscure the ground if the precipitation rate is high.

Precipitation is, relatively speaking, a rare phenomenon, for the number of hours per year with significant rainfall is less than 100 almost everywhere. It just seems to be raining all the time in some areas. Cloudiness is much more prevalent and therefore more important, as discussed earlier. Since radars and radiometers are usually effective through clouds, whereas cameras and infrared devices are not, microwave instruments are useful many more hours per year than are visible and infrared instruments.

RESOLUTION AND SYSTEMS

Spatial resolution of microwave systems usually is poorer than that of optical systems. Spatial resolution is determined by angular resolution, and angular resolution depends on the size of the aper-

ture in wavelengths. Since microwavelengths are much longer than optical wavelengths, the width of a microwave aperture can never contain as many wavelengths as the width of an optical aperture.

The ground resolution of a microwave system is often defined as the distance across the area illuminated by the antenna beam. The angular spread of the antenna beam is approximately the ratio of the wavelength to the antenna width, and the illuminated distance on the ground is the product of this ratio and r, the distance from antenna to ground. Thus, an antenna 1 meter in diameter gives a resolution r_a of 1 km at a distance of 10 km for a 10-cm wavelength; the ground resolution r_a is reduced to 100 m if the wavelength is reduced to 1 cm. If the antenna width can be increased to 10 m, a resolution of 100 m at 10 km is possible for a wavelength of 10 cm, and the ground resolution is only 10 meters for a 1-cm wavelength.

With antennas that can be readily accomodated on aircraft, resolutions usable for Earth resources monitoring can be achieved at distances out to 10 or 20 km. Thus, for the 5-m antenna shown in figure 9, the resolution on the ground is 10 m at a distance of 5 km. If this antenna is carried on a spacecraft at a distance of 500 km, however, ground resolution is 1 km. Even if the spacecraft antenna could be made 50 m long, the ground resolution would still be a full 100 m. The 1-cm wavelength of this example is about the smallest that can be used, and most spacecraft microwave systems use longer wavelengths and achieve poorer resolutions. Since the microwave radiometer can obtain resolution only by this method, it can never be used from spacecraft to produce high-resolution images. With radar, however, other techniques are available to achieve finer resolution.

Figure 10 illustrates four methods for achieving radar resolution. When an aircraft radar or microwave radiometer antenna is pointed to the side, as shown, a conical antenna pattern produces an ellipse of ground illumination. If angular resolution can be achieved only by use of the antenna pattern, as with the radiometer, fairly poor resolution results (upper left). Radars, because they can measure dis-

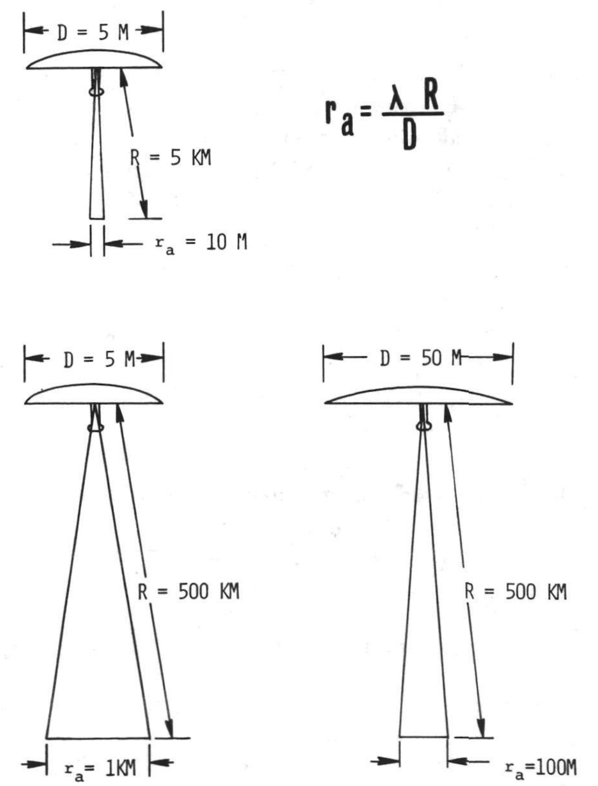


FIGURE 9. Antenna resolution from aircraft and spacecraft ($\lambda = 1$ cm).

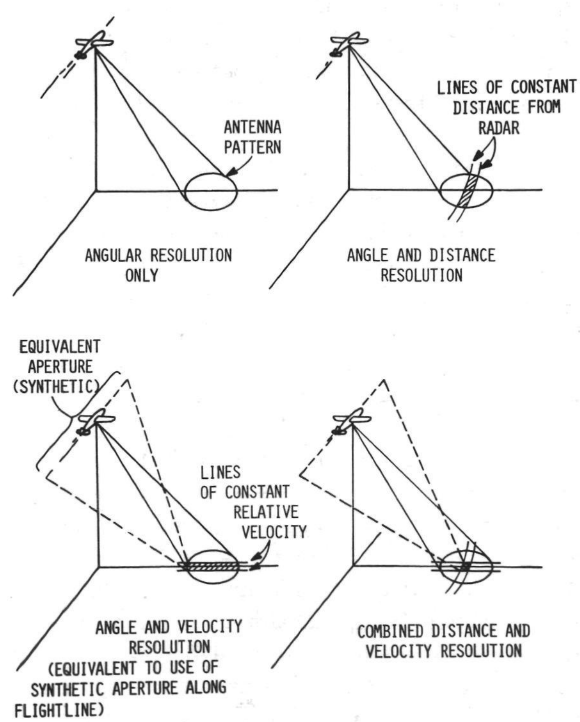


FIGURE 10. Radar resolution techniques.

tances, can achieve improved resolution, as shown to the right. The use of a short pulse for the radar illumination permits separating signals received from different distances. Thus, for the example shown, the ellipse of the antenna pattern is reduced to a narrow strip by a distance measurement.

In the sketch at lower left, measurement of speed is achieved by measuring shift, and this measurement is used to reduce the size of the observed region. Only the small region between lines of constant relative velocity contributes to the signal at any instant. We can show that this is equivalent in performance to a synthetic computer-generated antenna. Pulses are transmitted while the aircraft flies along the path illustrated, and the received information is stored in a memory aboard the aircraft; later the stored signals are processed to achieve an antenna beamwidth as narrow as that of a real antenna as long as the synthetic aperture. If the distance measuring technique and the synthetic aperture (or relative velocity measurement) are both used, the resolution can be greatly improved as shown in the sketch to the right. Thus, spacecraft radar systems can achieve ground resolution comparable to that of photographic systems, whereas spacecraft microwave radiometers cannot.

Let us now consider the operation of a microwave radiometer. The microwave radiometer is a radio receiver that is calibrated to detect small differences in the noise observed at its output. Some of the noise comes from the receiver itself, because of random motion of particles in the receiver components; the rest of the signal represents the scattered and emitted radiation from the ground.

The microwave radiometer works just like a radiotelescope. It is calibrated by switching alternately between the antenna on which the unknown signal is arriving and a source of noise with a controlled temperature; this controlled noise source is used as a standard of reference. As shown in figure 11, a switch connects the receiver output alternately to two different averaging systems; one is used when the standard noise source is connected to the input, and the other is used when the antenna is connected to the input. Before averaging, signals in the two channels vary so much, as shown in the sketch, that they cannot be separated. After averaging, however, fluctuations are much smaller, so that the difference can be measured between the signal

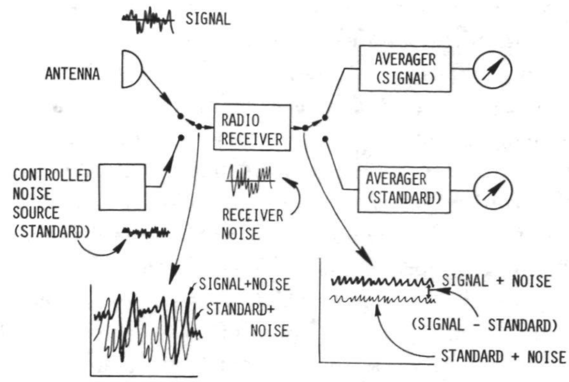


FIGURE 11. System block diagram of microwave radiometer.

coming from the upper averager, which contains the ground signal and receiver noise, and the signal coming from the lower averager, which contains the reference standard and noise. Thus, the measured difference shows the amount by which the effective temperature of the ground exceeds that of the standard reference controlled noise source.

The precison of measurement of the microwave radiometer depends on the length of time available for averaging and on the bandwidth of the radio receiver. Ideally, both the bandwidth and the averaging time would be very large. If the bandwidth is too large, however, interfering signals from radio and radar stations will enter the receiver and be confused with thermal emission from the ground. The averaging time is limited because the aircraft or spacecraft can view a particular spot on the ground for only a limited time before it passes on to other terrain. Thus, for a given bandwidth, the precision is better for a slow vehicle than for a rapid one.

A simple radar system (figure 12) consists of a transmitter, a receiver, and a display, with some kind of synchronization between the transmitter

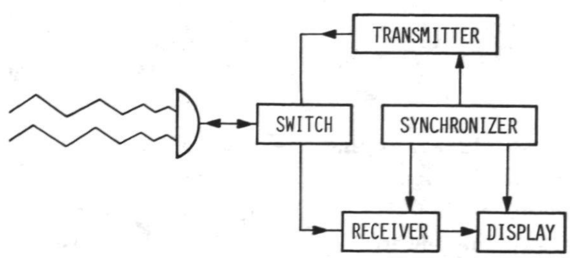


FIGURE 12. Radar system block diagram.

and the receiver. A scatterometer may not even need synchronization. Most radar systems transmit pulses (short bursts of rf energy). The transmit-receive switch connects the transmitter to the antenna; the signal goes out and illuminates the target, and the scattered signal returns to the antenna. By this time the transmit-receive switch has changed position, so the signal is conducted through it to the receiver. At an appropriate time, the synchronizer provides a pulse to the display which causes a sweep on its cathode ray tube. The output of the receiver usually varies the brightness of the spot on the display tube.

The side-looking airborne radar (SLAR) is the most important radar system for Earth observation. Figure 13 shows the operation of a real-aperture SLAR. The long axis of the antenna (A) is along the flight direction, producing a narrow beam (B) that points toward the side. Individual targets within the beam are separated by distance measurement. The receiver output (C) is shown as it would be displayed on an oscilloscope. It is stronger at point *a* because of the trees there, at point *b* because of the bridge, and at points *c* and *d* because of two groves of trees close to one another. This signal is used to vary the brightness of a scanning spot on a cathode ray tube (D), which is imaged onto the emulsion (E) of a photographic film (F). The film is moved past the tube in synchronization with aircraft motion, just as with the infrared line scanner. The result is an image of the ground.

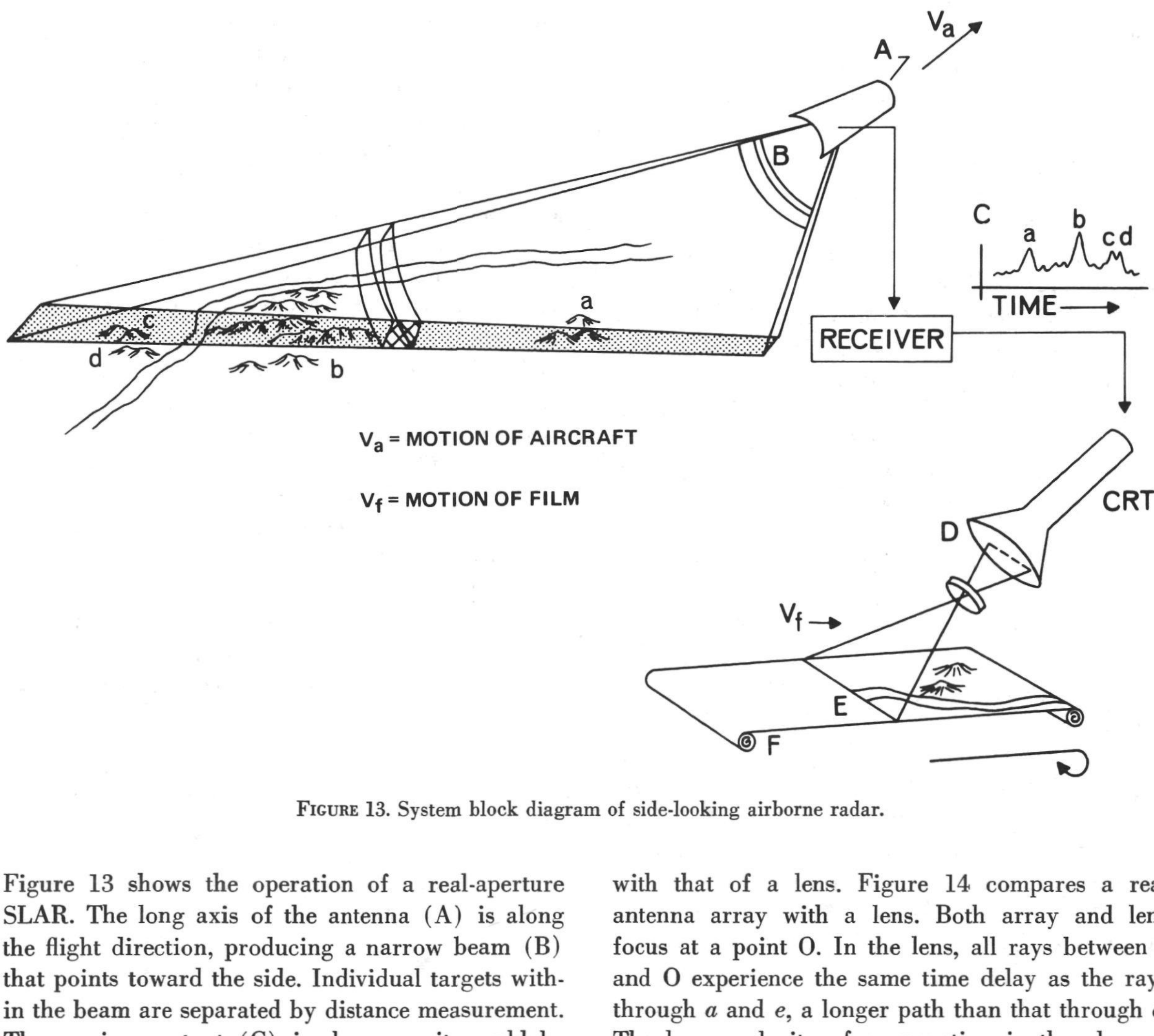
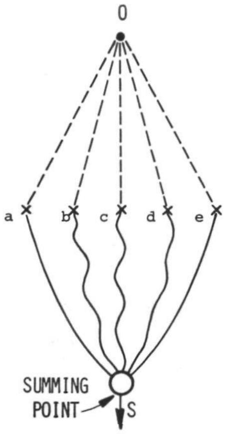


FIGURE 13. System block diagram of side-looking airborne radar.

The synthetic-aperture (Doppler beam-sharpening) technique must be used to achieve fine resolution at long distances. One way to consider the synthetic aperture is to compare its performance with that of a lens. Figure 14 compares a real antenna array with a lens. Both array and lens focus at a point O. In the lens, all rays between I and O experience the same time delay as the rays through *a* and *e*, a longer path than that through *c*. The lower velocity of propagation in the glass of



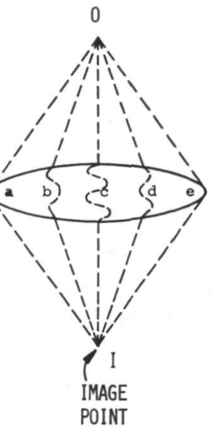


FIGURE 14. Comparison of full-focused synthetic array with lens focused at point O.

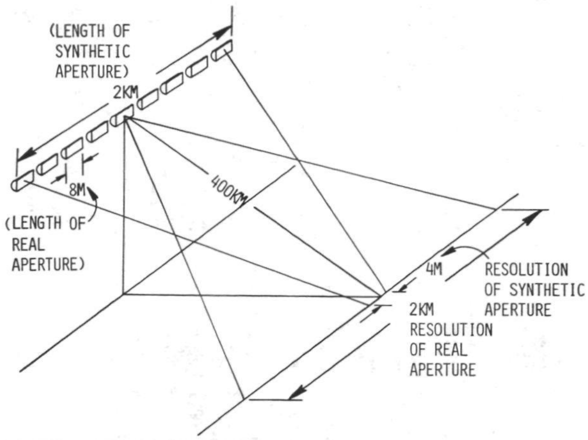


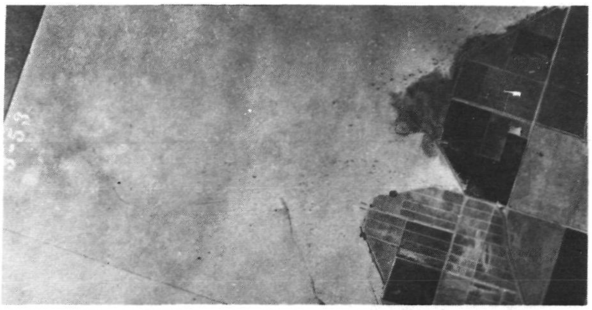
FIGURE 15. Along-track resolution of real aperture ($r_a = \lambda R/D$) compared with synthetic aperture ($r_a = D/2$) for 4-cm-wavelength spacecraft radar.

the lens compensates for the shorter path through *c*, so that all time delays are the same. In the equivalent real-aperture antenna, the extra delay is achieved by using a transmission line longer than geometrically necessary between point *c* and the summing point. In the synthetic aperture, points *a*, *b*, *c*, *d*, and *e* are occupied at different times as the aircraft flies along. The returned signal, including phase information, is stored in a memory. Actually, the memory is usually a film somewhat like a hologram. After the aircraft reaches *e* (and usually after it returns to base), the signals are processed. They produce the same phase sum as would the array pictured, with the same result as for a lens. In fact, processing the film often involves passing laser light through the "hologram" and through appropriate lenses.

The real aperture of the antenna achieves the ground resolution indicated by the equation $r_a = \lambda R/D$, discussed previously. Theoretically, a synthetic aperture system may achieve a ground resolution independent of distance, since the width of the synthetic antenna increases as the distance increases. Hence, the angular width of the beam due to the synthetic aperture decreases at the same rate, and the resolution does not depend on distance. Figure 15 shows a spacecraft synthetic aperture 2 km long that is made up of successive transmissions from a spacecraft antenna whose actual width is only 8 m. The width of the region illuminated on the ground by the 8-m antenna at a distance of 400 km is 2 km, which would be the resolution of a microwave radiometer using such an antenna. The synthetic aperture, however, can in theory achieve a radar resolution of only 4 m, as indicated. In practice, achieving this kind of resolution at long distances requires an extremely stable system, both for the electronics and the vehicle.

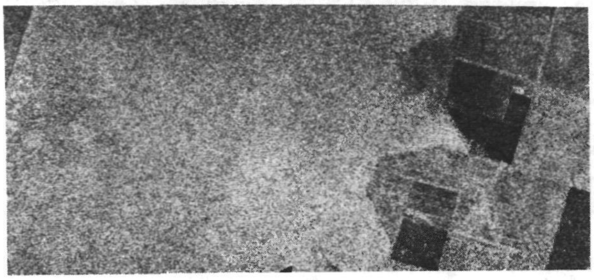
One difficulty with radar images is illustrated by figure 16. The monochromatic illumination of the radar, along with the resulting phase interference patterns, produces a speckled image. The figure shows an aerial photograph reproduced with white light, the same photograph reproduced with a laser (monochromatic) source, and a real-aperture radar image of the same area. The random phase interference phenomena associated with the grains in the original film create the speckled appearance in the laser-produced image; a similar appearance would have existed for an image made by a synthetic-aperture radar. The real-aperture radar averages several independent samples from this phase interference pattern, so the image is not as variable as the laser image, but it is not as good as the white-light image.

To reduce the speckling of the image, one must average together many independent samples. The real-aperture radar averages several samples in the direction of flight in producing its image. The number is twice the ratio of its resolution to its aperture



MONOCHROMATIC AIRPHOTO

MONOCHROMATIC RADAR



PANCHROMATIC AIRPHOTO

FIGURE 16. Comparison of monochromatic and panchromatic airphotos with monochromatic radar image.

size. Thus, for a 10-m resolution and 5-m aperture, four samples are averaged. A fully focused synthetic aperture, on the other hand, produces only one independent sample.

Additional independent samples can also be obtained by using excess bandwidth, as does the white-light photograph. Since some bandwidth is required for the range resolution (approximately the reciprocal of the pulse duration), the number of independent samples that can be averaged is equal to the ratio of the bandwidth actually used to that needed for range resolution. Thus, 10-m slant-range resolution uses about a 15-MHz bandwidth; if 150 MHz is used, 10 independent samples may be averaged.

EXAMPLES OF APPLICATIONS OF RADAR

The most extensive use of radar for mapping has been the well known project in Darien Province, Panama and the adjacent part of Colombia. The radar mosaic shown in figure 17 was prepared for the U.S. Army Corps of Engineers in cooperation with the government of Panama, from images obtained during 8 hours of flying. In these 8 hours, each point on the mosaic was imaged from four different directions. Attempts had been made for a quarter of a century to map this area using photography, and only a small fraction had ever been mapped because continuing cloud cover prevented photography most of the time.

Figure 18 is a topographic map prepared from the radar images. It has contour intervals of 100 meters and is far more accurate than any previous map of this difficult terrain. Figure 19 shows a geologic map prepared by Dr. Harold MacDonald on the basis of the radar images and other data, including ground checks at points that could be visited. It is certainly the most complete geologic map of the area, although additional ground checking would be helpful. Figure 20 is a geomorphic map of the area, illustrating the landform regions found. It too was prepared from the radar images.

The Panama study illustrated the value of radar in updating coastal maps. Figure 21 shows a sample of the radar image and an earlier map of the same area along the coast of Panama. Notice the changes that have occurred and how clearly they are indicated on the radar image.

We at the University of Kansas have been studying the use of radar for mapping vegetation in farming areas and elsewhere. Our test site at Garden City in western Kansas is an agricultural region, as indicated in figure 22. The large outlined area contains 400 fields. Every time the radar aircraft flies over the test site, the fields are sampled to determine the crops, moisture content, and other relevant parameters.

A brief study compared the ability of two polarizations of radar and two colors of photography to distinguish crops in this area. For this one test, the radar proved superior in separating sugar beets, corn (known as maize in Europe), and bare ground very clearly. On the other hand, the photographic images clearly distinguished uncut alfalfa. Hence, the combination of radar and photograph permitted

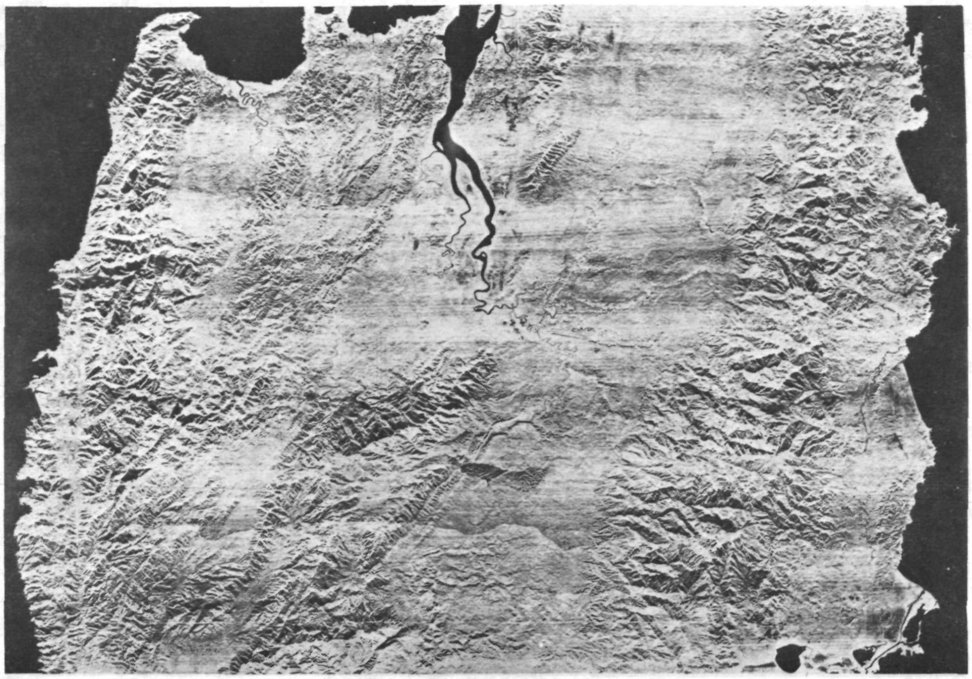


FIGURE 17. Radar mosaic of Darien Province (Republic of Panama) and northwest Colombia.

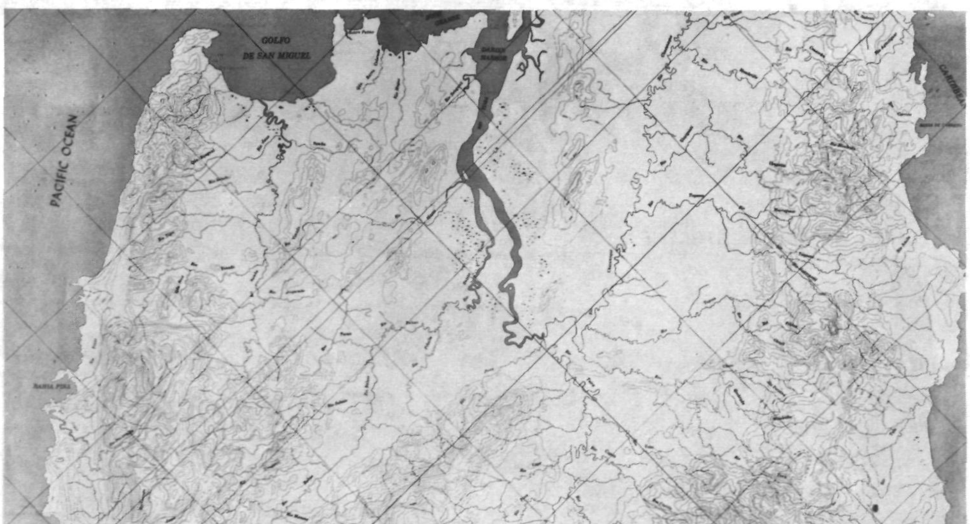


FIGURE 18. Topographic map of Darien Province, Panama, derived from radar (prepared by Raytheon Autometric).

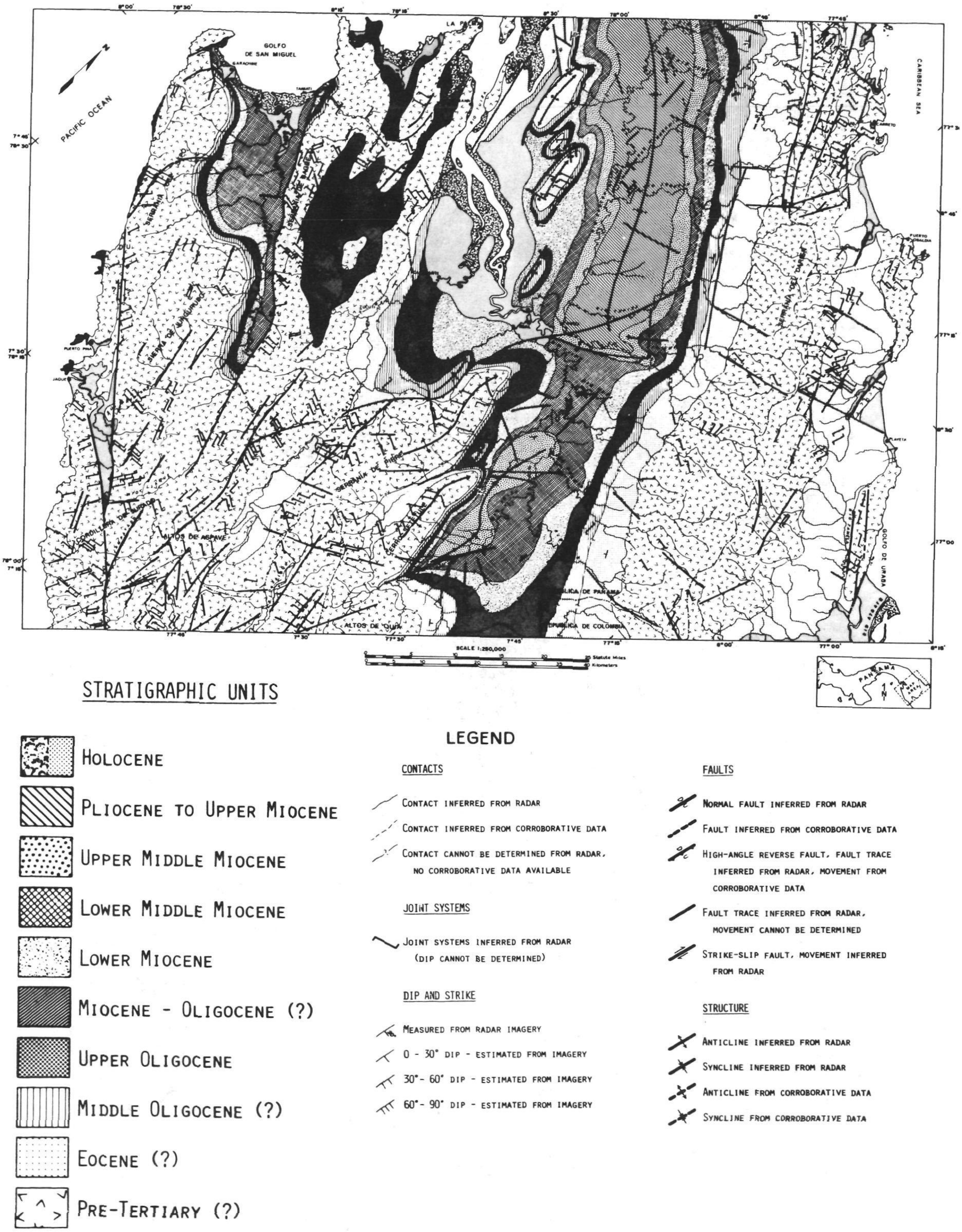


FIGURE 19. Geological reconnaissance map of Darien Province (Panama) and northwestern Colombia.

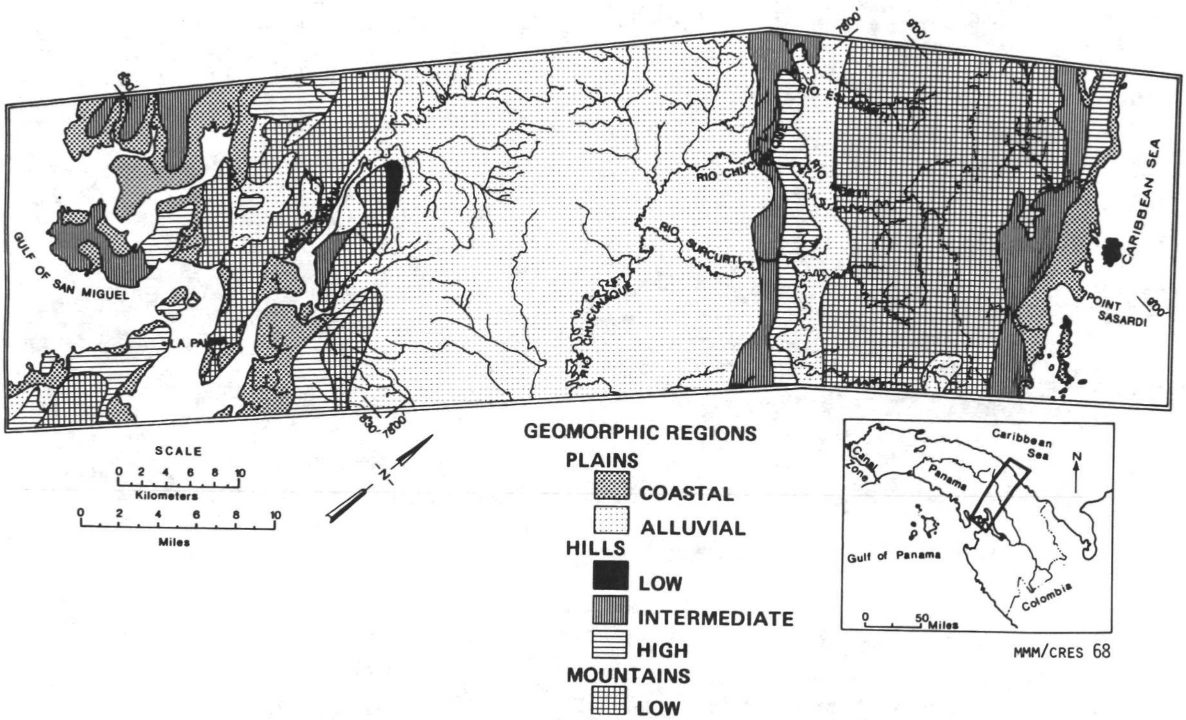


FIGURE 20. Radar-derived geomorphic regions in area of possible route for sea-level canal, Panama.

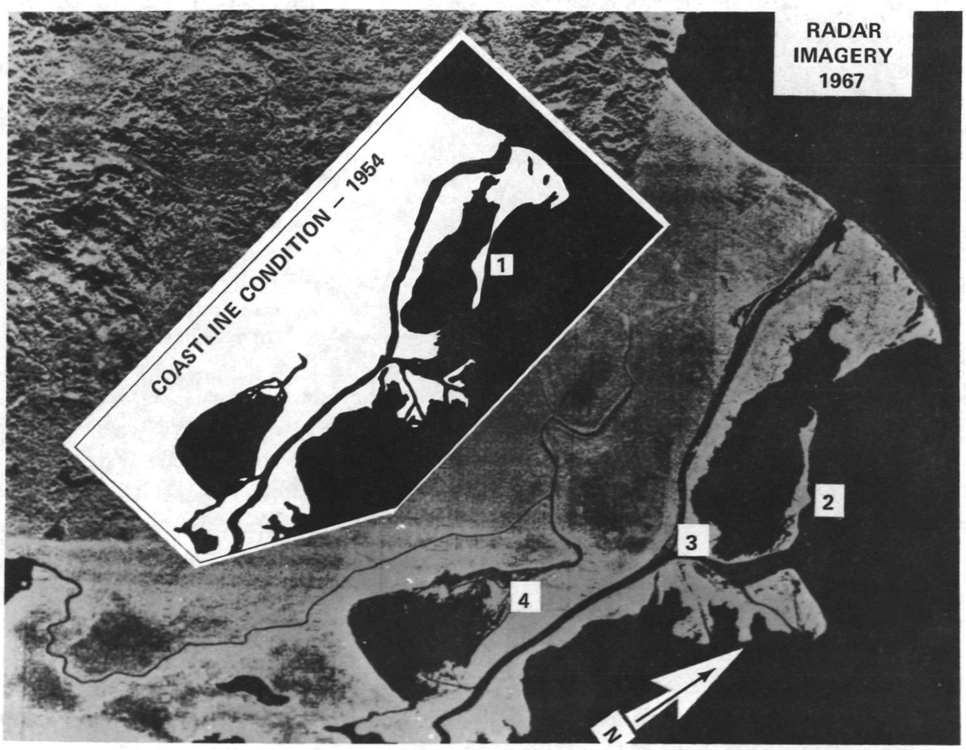


FIGURE 21. Coastline changes are easily mapped with radar imagery. 1 and 2—change in landward attachment of spit from 1954 to 1967. 3—Vegetation in the channel indicates it is being abandoned. 4—Lake filling by sedimentation.

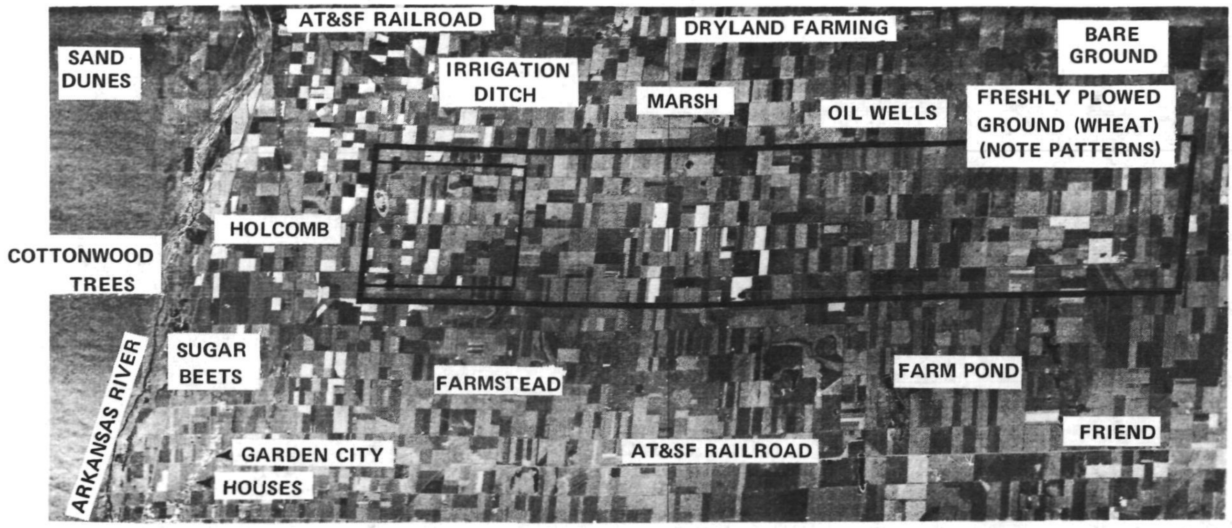


FIGURE 22. K-band radar image of Garden City test site, Kansas (September 1965).

clear distinction of three crops and of bare ground without crops.

To assist field workers in using radar images, we are now developing dichotomous keys, such as the example shown in figure 23. A relatively untrained observer in the field can take the radar image and, following this key, decide what crops are growing in a particular field.

Radar is now receiving extensive use in geology. Only one example, other than the Panama geologic map, is given here. The Roselle lineament in eastern Missouri was identified on radar imagery. Figure 24 shows the location of the lineament, which consists of a portion identified on the radar and other portions identified in terms of extreme characteristics and mapped faults. The shaded areas represent extensive lead and zinc mining. Geologists from the mining companies are interested in this find because it may help locate new deposits of minerals.

Since the microwave dielectric properties of soil are strongly dependent on the moisture content, one would expect that radar should be able to distinguish soil moisture. This is indeed the case at angles of incidence near the vertical, where the radiation can penetrate between the plants and reach the soil. In figure 25 the moisture pattern shows clearly in the near range portions of the images (near the aircraft), the dark and light portions of the image being wet and dry soils respectively. In the far portion of the image, where the rays are more nearly horizontal, most of the signal apparently is caused by scatter from the vegetation, and the details of the soil moisture are lost.

IDENTIFICATION OF CROP TYPES
AT GARDEN CITY, KANSAS
(DERIVED FROM RADAR IMAGERY)

A. FIELD HAS HIGH RETURN (POSITIVE,HH)
  B. HH TONE HOMOGENEOUS
    C. TONE SHIFT HH (LIGHTER) TO HV (DARKER)
      D. SHIFT NOT PRONOUNCED
        E. HV TONE HOMOGENEOUS -- SUGAR BEETS
        EE. HV TONE NOT HOMOGENEOUS -- FALLOW
      DD. SHIFT PRONOUNCED
    CC. . . . . CONTINUED

FIGURE 23. Example of dichotomous key produced from radar to aid identification of crops and to expedite creation of pattern recognition algorithms.

Figure 26 shows a vegetation map of the Horsefly Mountain region in Oregon, prepared on the basis of preliminary study of the radar images and some field work. It compared very favorably with a map previously obtained by means of an extensive field survey by the U.S. Forest Service. Because of changes in vegetation patterns in the period between the survey by the Forest Service and the obtaining of radar imagery, the radar map was more accurate in some places than the Forest Service map.

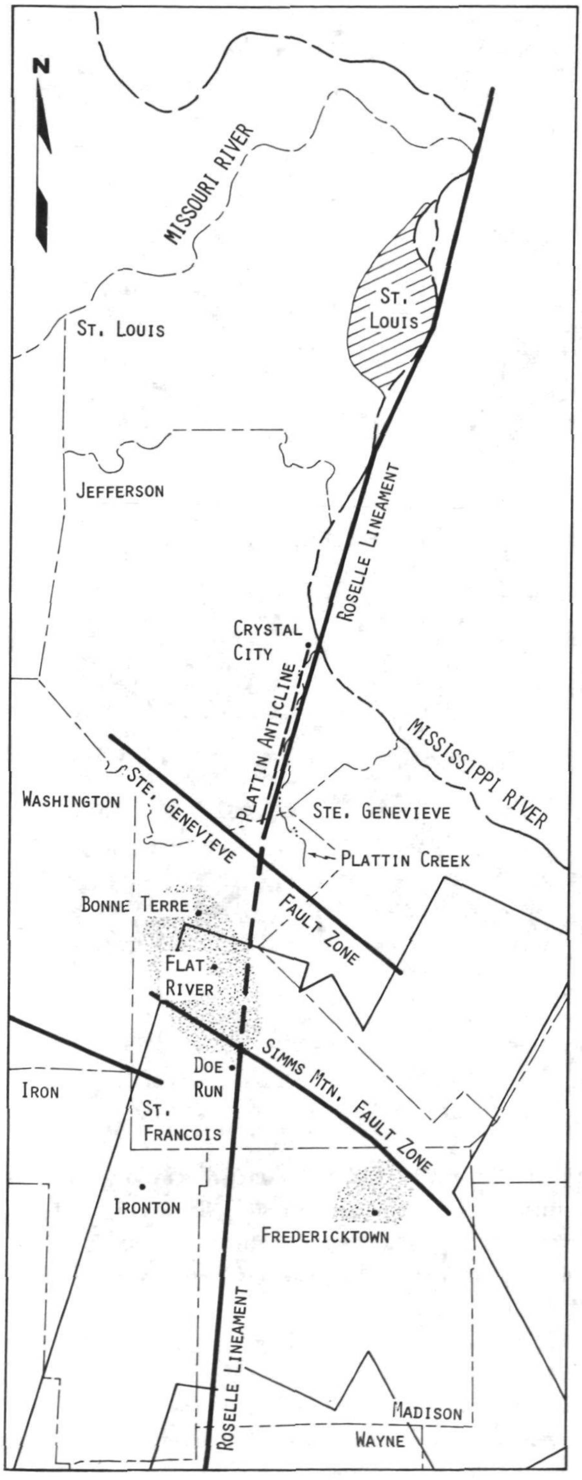


FIGURE 24. Relationship of Roselle lineament to mineral districts (lead-zinc).

Several observers have used radar in experimental studies of land use and of soil type. Barr, at Purdue, made an extensive survey of the use of radar for engineering soils interpretation. Figure 27 shows an example of interpretation from radar imagery of a region in Wyoming, in which nine different categories of surface materials have been identified.

Although most applications of radar to the Earth sciences and Earth resources studies will always use imaging systems, the radar scatterometer and microwave radiometer are both useful for studying the ocean, where fine resolution is not always required. In particular, radar scattering at a wavelength of about 2 centimeters seems to be correlated closely with the very small capillary waves on the ocean, and consequently with the wind speed to which these waves respond. Figure 28 shows the results of three years of measurement by NASA Houston, using a 2.25-cm radar scatterometer over the ocean. Although some points are uncertain, perhaps due to errors in reporting the wind rather than in the signal, the relationship between radar cross section and wind speed is clear and should produce a very useful instrument for determining the winds over the world's oceans from a satellite.

EXAMPLES OF RADAR SYSTEMS

The range of choices available to the radar designer is extremely great, since many parameters can be adjusted. Let us conclude by examining an aircraft real-aperture SLAR that has been used to produce many of the images presently available, along with a group of SLARs that might be usable on spacecraft.

The table shows the parameters of the real-aperture SLAR used extensively in the NASA program and now being used commercially. To achieve good azimuth resolution with a reasonable antenna size (5-m aperture), the frequency is 35 GHz (wavelength 0.86 cm). Although the transmitter peak power is 100 kW, the average power is only 3 kW. The maximum swath width is about 20 km at an altitude of 6 km. Note that the azimuth resolution varies from under 9 m at a slant range of 5 km to 35 m at a slant range of 20 km. The slant range resolution is always 12 m; ground range resolution depends upon angle of incidence. Because the number of independent samples increases with slant

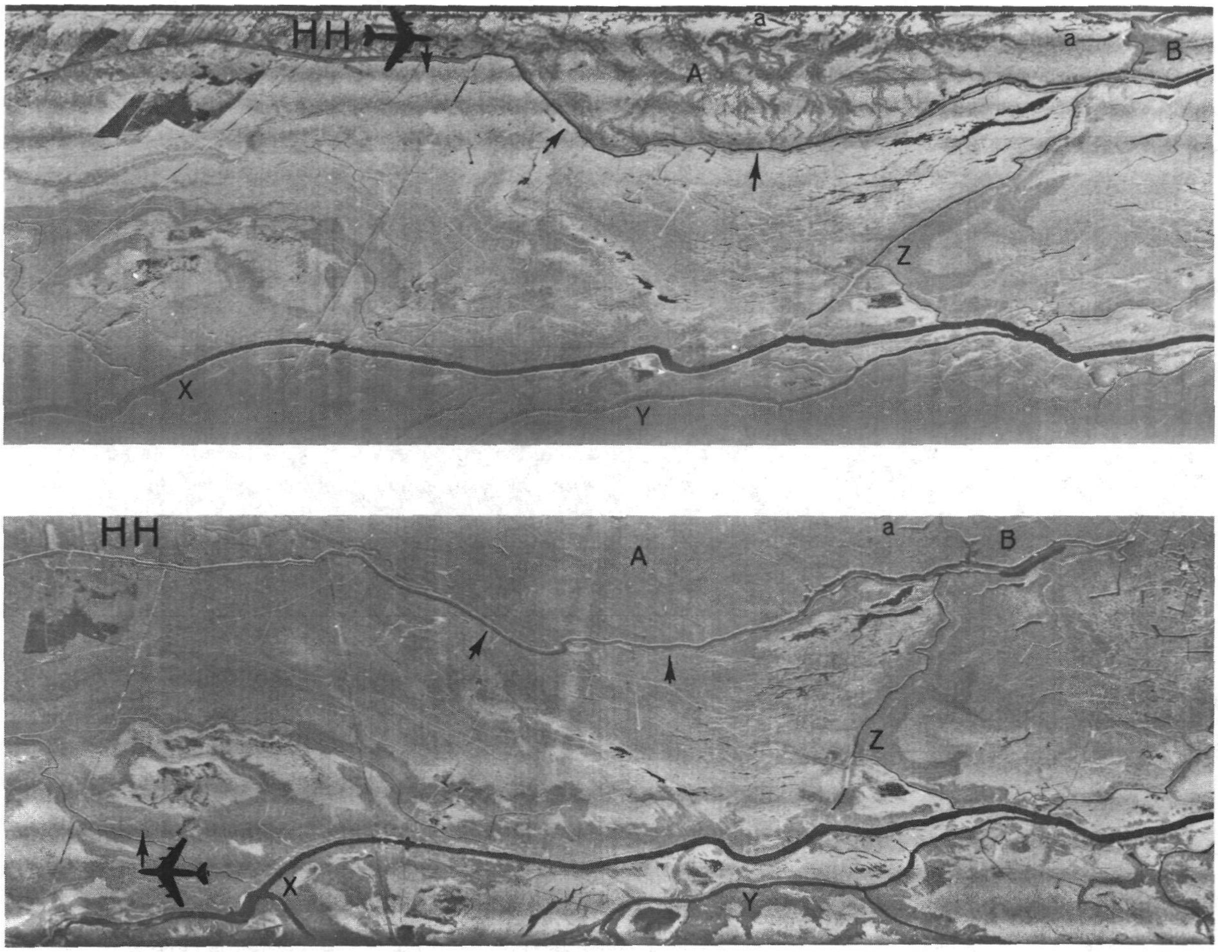


FIGURE 25. Radar images of area south of Baton Rouge, Louisiana. Tonal reversals in the near-range portions of the images (A and B) are due to soil moisture content. Their absence in the far range results from the dominance of vegetation return.

Performance parameters of typical aircraft real-aperture SLAR

Slant range (km)	Azimuth resolution (m)	Slant-range resolution (m)	No. of independent samples	$\frac{\sigma}{\overline{W}_r}$
5	8.8	12	3.5	0.53
10	17.6	12	7	0.38
15	26.4	12	10.5	0.31
20	35	12	14	0.27

range, the ratio of the standard deviation σ of the return to the mean return power $\overline{W}_r$ decreases from over half to just over a quarter. Thus, at the outer edge of an image, the picture is less grainy than at the inner edge.

The SLAR described above is an elaborate and expensive system that produces high-quality images. Like most other side-looking airborne radars, it was developed for military use. Relatively simple systems could be developed for civil use on fairly small aircraft, and we believe the cost should not be high. So far, none of these has been made available, but modifications of existing aircraft radars should be possible at minimal expense.

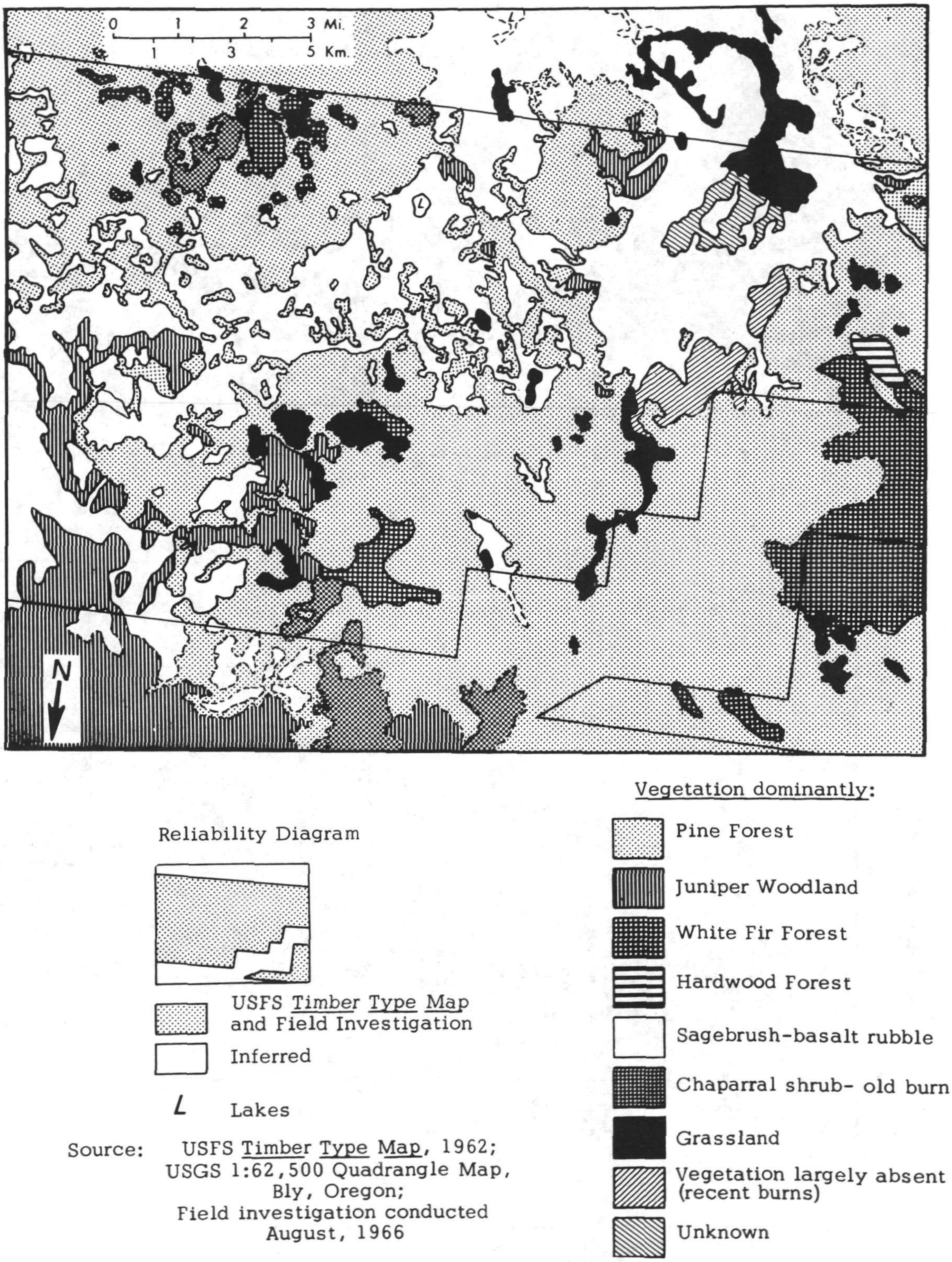


FIGURE 26. Vegetation type mapping prepared from radar imagery.

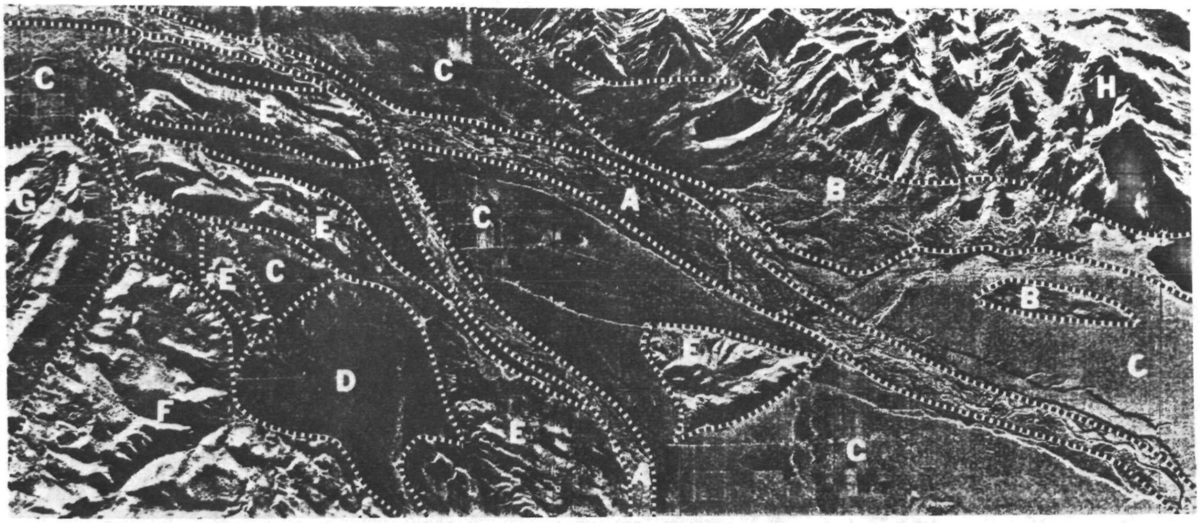


FIGURE 27. Radar image of Wyoming area used for identification of surface materials (from Barr and Miles).

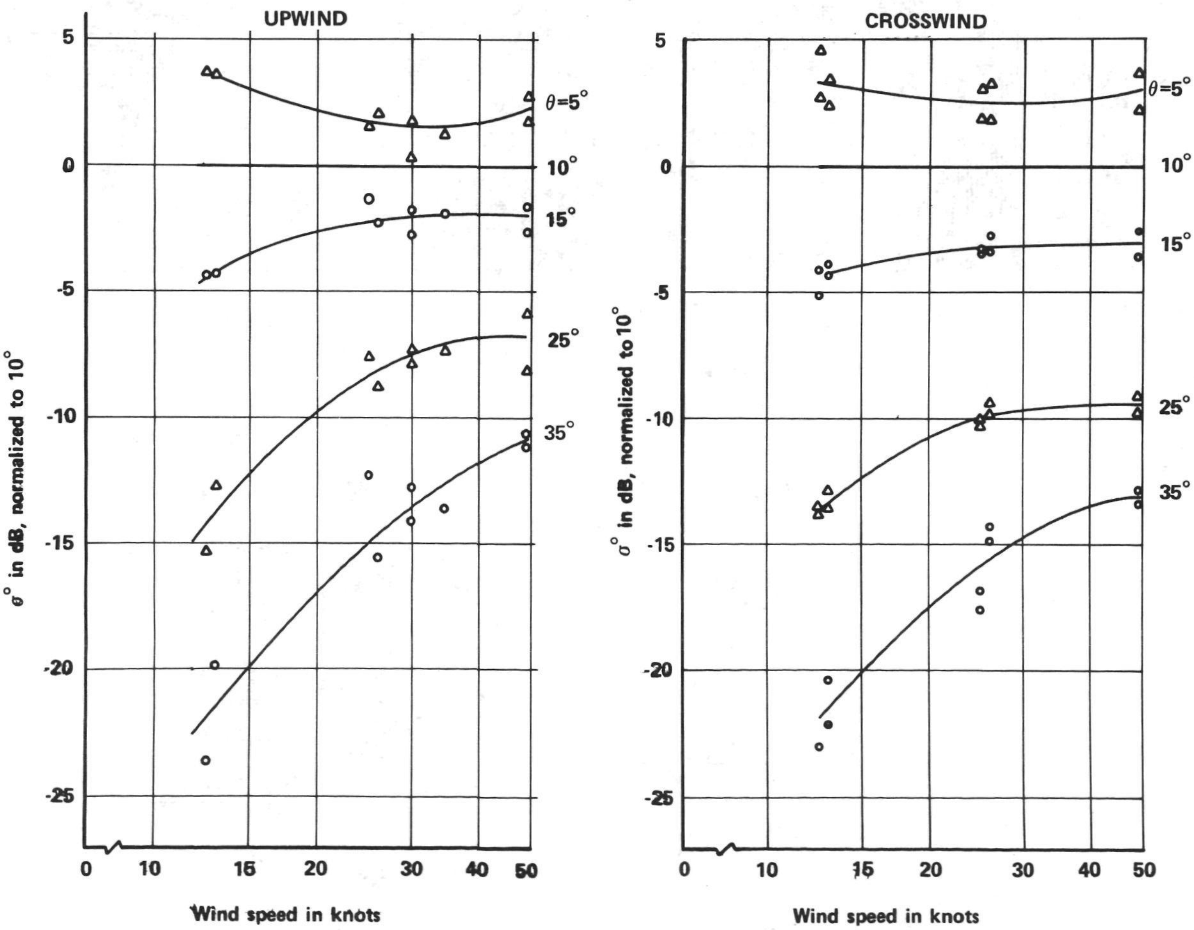


FIGURE 28. Radar scattering cross section, $\sigma°$, as a function of wind speed for 13.3-GHz radar over ocean areas.

Parametric studies of spacecraft imaging radars have been made. All such radars must use synthetic aperture because of the resolution problem. The satellites considered have ranged in size from Nimbus, the weather satellite, to the proposed space station. Antennas also come in many sizes, from as short as 3 m to as long as 20 m, and from only 50 cm high to 3 m high. Depending upon the particular satellite and the power available, the resolution one might expect could be between 100 and 10 m.

CONCLUSIONS

Microwave systems, whether radars or radiometers, are nearly always usable because they work day and night, whether the sky is clear or cloudy. Many uses of radar imaging have already been demonstrated for mapping resources, yet research has only begun and additional uses can be expected as more researchers work with radar images. Systems for producing such images may be large or small because the designers have many tradeoffs available. Large systems will have fine resolution, long range, and multispectral capability. Small systems will have poorer resolution and be confined to a single wavelength.

Microwave radiometers are more sensitive to weather phenomena than radars, but this is an advantage in that they can be used as meteorological sensors to determine the properties of the atmosphere that are obscured to visible and infrared sensors.

Resolution problems are severe at microwavelengths when the beamwidth of the antenna must be used to define the resolution cell, as it must with a radiometer. Radars, however, can combine ranging and velocity measurements to make a synthetic aperture much larger than the real aperture, providing much finer resolution. Such systems can be used aboard aircraft or spacecraft to provide an inportant supplement to visible-range sensors in good weather and provide the only sensor usable in bad weather.

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SESSION VII

Chairman: Theodore C. Byerly

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The Interpretation of Spectral Data

MARVIN R. HOLTER

Chief, Earth Observations Division,
Manned Spacecraft Center, NASA

The two most important problems in remote sensing are too little information and too much information. I will explain this apparent contradiction.

The usual methods of remote sensing are aerial photography and the use of the human eye from aircraft. Both of these methods produce less information than we would like to have. We all know that there are many things in nature that do not exhibit high contrast in photography or to the human eye. For example, all vegetation appears very nearly the same shade of green. We do know from measurements with spectrometers that increased contrast is available in other parts of the spectrum. That is the basic reason we are exploring so intensively the use of nonphotographic sensors in the ultraviolet, infrared, and microwave parts of the spectrum. The problem is too little information with the older methods; the solution is to develop and use, in addition to photography, other sensors.

On the other hand, even a fairly modest camera system can produce more information than any reasonable number of human beings can interpret in a short period of time. The human being is a very slow instrument to do complete interpretations of photographic or nonphotographic images.

One method of solving the problems I have mentioned is to automate or use computers for some part of the interpretation process.

In remote sensing, we are concerned primarily with sensors of electromagnetic radiation. The major characteristics of electromagnetic radiation include distributions of radiant color with wavelength. In the visible range, we see color. We cannot see other regions of the spectrum, but there are wavelength differences which can be used for recognition and discrimination.

A second characteristic of electromagnetic radiation is its distribution in space, normally called shape information, which enables us to recognize things. A third characteristic is radiation changes with time. There are two types of time change. If an object is moving very rapidly, the frequency or wavelength of its radiation is shifted. The second time-change effect is a slow one which can be detected by time-lapse photography.

I am concerned today with the spectral characteristic of radiation and how we interpret resultant spectral information in the outputs of sensors. First, however, I will make one remark with regard to shape or spatial recognition.

It is too easy for many to believe that the finest spatial resolution obtainable is the best resolution to work with, and I would like to give just one example where the best resolution is much coarser than the finest obtainable. In figure 1 you see on the left a picture of an attractive young lady. On the right, at much higher magnification, is a picture of one square centimeter of skin on her arm. Now, if I were a medical man interested in dermatology, I might prefer the resolution at right, but for the ordinary man the much coarser resolution at left is preferable.

Figure 2 is a diagram of electromagnetic radiation, which at a single instant of time consists of an electric field, drawn here in the vertical plane. An electric field moving through space will always be associated with a magnetic field at right angles

FIGURE 1. High resolution is not always preferable to low resolution. Photo at left has more general appeal than much higher resolution photo at right showing 1 cm² of skin on the girl's arm, although the latter might be of interest to a dermatologist.

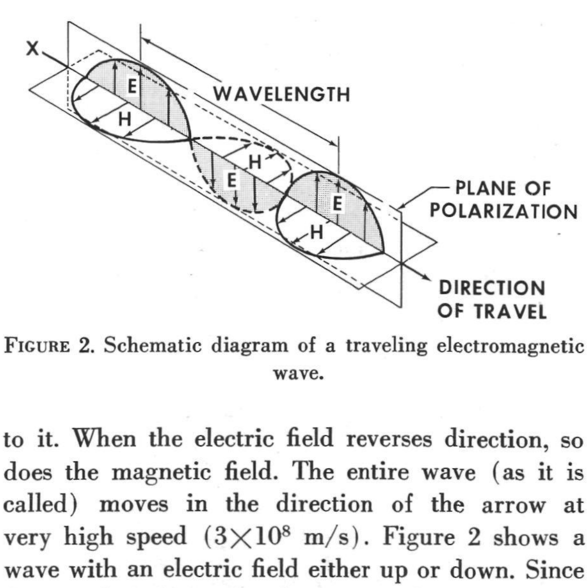


FIGURE 2. Schematic diagram of a traveling electromagnetic wave.

to it. When the electric field reverses direction, so does the magnetic field. The entire wave (as it is called) moves in the direction of the arrow at very high speed (3×10^8 m/s). Figure 2 shows a wave with an electric field either up or down. Since that is the plane of polarization, this is a plane-polarized wave. It is possible to have many bits of radiation, some with the electric field as shown and some with electric fields in many different planes. In the latter instance, the wave is unpolarized.

Wavelength multiplied by frequency is equal to the speed of light, and this relationship can be expressed in many different ways. For example, a 1-μm wavelength corresponds to a frequency of 3×10^{14} Hz. Similarly, a 1-meter wavelength corresponds to a frequency of 300 MHz.

The spectral sensitivities of the sensors we have available are shown in figure 3 and the table. Ordinary film is sensitive to only a very small portion of the infrared band. Other types of sensors are sensitive to the entire optical region. Because the atmosphere is highly absorbing at wavelengths between 15 μm and 1 mm, that band is not used very much. The useful optical spectrum ranges from 0.3 μm to 15 μm. In addition, we have passive microwave devices operating in the 1-mm-to-10-cm region, approximately, and active radars operating at wavelengths from 1 mm to as long as 10 meters.

Factors that influence radiation are shown in figure 4. In remote sensing, we must understand these factors to learn something about an object from a signal measured at a point some distance away. Characteristics of a signal will depend on the

Wavelength and frequency ranges of operation for remote sensors

	Spectral region	Band	Wavelength	Frequency	Common applicable imaging sensors
	Microwave	Active (radar) { (UHF) (SHF) Passive	10 cm to 1 m 1 to 10 cm 1 mm to 1 cm	300 MHz to 3 GHz 3 to 30 GHz 30 to 300 GHz	Scanning antennas with radio frequency receivers
	Infrared	Far IR Intermediate Near IR	8 μm to 1 mm 3 to 8 μm 0.78 to 3 μm	300 GHz to 37.5 THz 37.5 to 100 THz 100 to 385 THz	Scanners with infrared detectors; various image tubes (not very satisfactory)
		Near IR	0.78 to 3 μm	100 to 385 THz	Photographic film to approx. 1 μm; scanners with infrared detectors; various image tubes
Optical	Visible		0.38 to 0.78 μm	385 to 789 THz	Photographic film; scanners with photomultiplier detectors; television
	Ultraviolet	Near UV Intermediate UV	315 to 380 nm 280 to 315 nm	789 to 952 THz 952 to 1008 THz	Photographic film; quartz lenses; scanners with photomultiplier detectors; image-converter tubes
		Far UV Vacuum UV	100 to 280 nm 4 to 100 nm	1008 to 3000 THz 3000 to 75 000 THz	These wavelengths do not penetrate the Earth's atmosphere significantly to be useful for agricultural remote sensing.

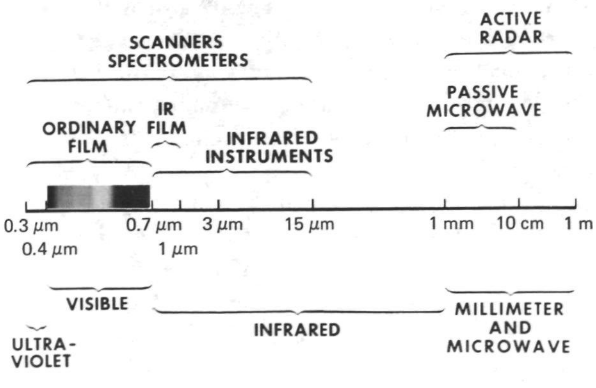


FIGURE 3. Spectral sensitivities of various sensing instruments.

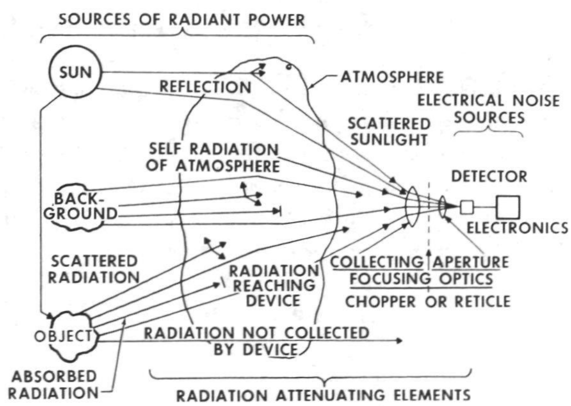


FIGURE 4. Diagram of radiation processes.

source, reflecting properties of the object, absorbing and scattering properties of the atmosphere, and at some wavelengths radiation from the atmosphere itself added to that from the object. The three major effects of the atmosphere are absorption, scattering, and emission in the infrared wavelengths.

What is commonly called the signature of a target basically depends on the spectral reflectivity and emittance of a material. These properties vary with the angles of illumination and observation. Figure 5 illustrates one spectral signature by showing re-

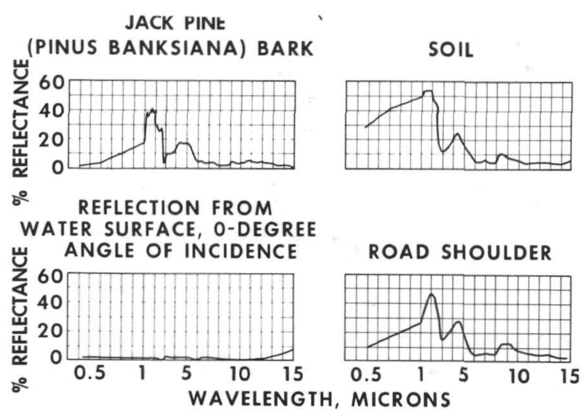


FIGURE 5. Reflectance spectra of selected materials.

flection as a function of wavelength for the bark of a tree, two types of soil, and water. If we make observations in such a manner that we can sense differences in the amount of radiation reflected at indicated wavelengths from these materials, we can separate or discriminate the materials and perhaps identify them specifically. Thus, the entire process of spectral discrimination or recognition depends on an understanding of reflectivity and emissivity curves.

Now let us take a look at some photographic spectral discriminations. Figure 6 shows one area in the western United States at several different times of day. The differences in spectral signatures are observable in black-and-white reproductions, but they are even more impressive in color. Before dawn, for instance, water in the stream looks approximately the same color as just after dawn; but later in the morning it looks blue, which is quite a different color. Its blueness is due to strong side lighting. With back lighting at different times of day, it looks quite different again, and it becomes slightly reddish after sunset. Similar changes take place in all parts of the picture. Fortunately, the manner of change is predictable when the illumination source is sunlight. Figure 7 indicates changes with time of year. These pictures vary in their utility for estimating the ability of the area to support animals that eat grass.

Figure 8 shows two sets of curves. The upper set represents the regions of the spectrum used in ordinary color film and also black-and-white film when different filters are employed to record color. A No. 47 filter will isolate one part of the spectrum, and that is essentially the part of the spectrum recorded on blue emulsion in color film. A No. 58 filter corresponds to the green emulsion in film, while a No. 25A filter isolates the red portion. A No. 25A filter will transmit beyond 7 μm, but the film sensitivity drops off at that point, as shown by the dashed curve. The figure also shows three corresponding curves for infrared color film.

Figure 9 diagrams the mechanism of operation of black-and-white film. The upper bar shows colors to be recorded. The center bar represents a single layer of panchromatic film, and the lowest bar indicates the density of film resulting from the spectral sensitivity of its emulsion and the incident radiation. Figure 10 shows a corresponding diagram for ordinary color film. In this case the center bar representing the film is of three layers, each sensitive to a different color. The upper layers also act as filters, screening certain wavelengths from the lower layers.

Figure 11 is a corresponding diagram for infrared Ektachrome film. This film consists of three layers sensitive to green, red, and infrared wavelengths. Blue dye is in the green-sensitive layer, green dye in the red-sensitive layer, and red dye in the infrared-sensitive layer. This results in a so-called false color image in a photograph because the image colors differ from colors observed by a normal human eye.

Figure 12 shows some pictures made with various films. The upper left, upper right, and lower left images are of one scale. Unfortunately, the lower right image is of a different scale and shows a larger area than the other three images. It was also made at a different time of year than the other three. We can see that for this geological application ordinary aerial Ektachrome film shows more

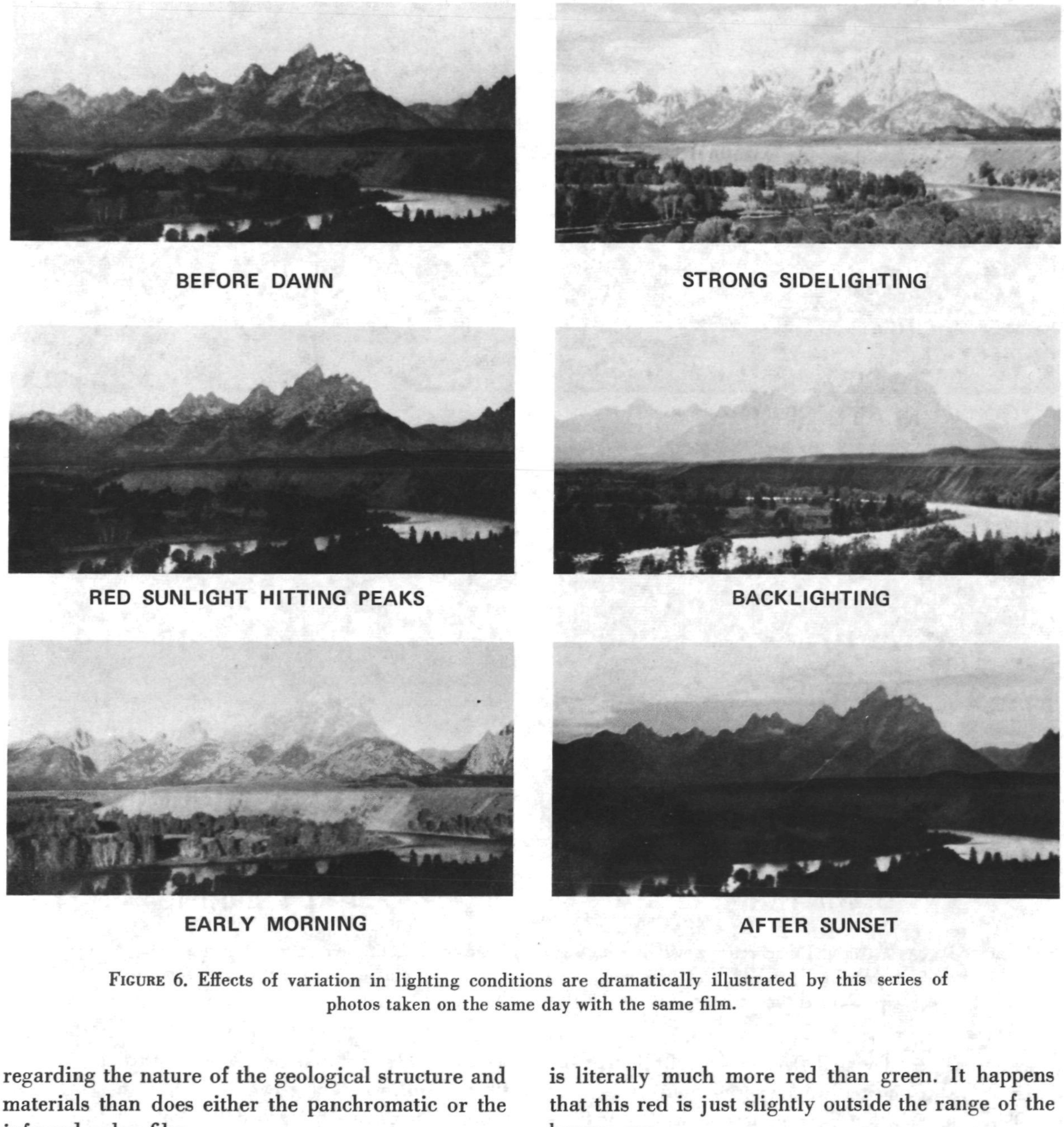


FIGURE 6. Effects of variation in lighting conditions are dramatically illustrated by this series of photos taken on the same day with the same film.

regarding the nature of the geological structure and materials than does either the panchromatic or the infrared color film.

Figure 13 shows the two types of film again. The left photo in each pair was made with ordinary color film, while those on the right are from infrared color film. There are two major differences here. The vegetation appears red in the infrared color photos, if it is healthy, because the reflectivity of vegetation is very high just outside the visible in the very near infrared. In fact, it is higher by a factor of four than in the green. Therefore, all of the vegetation is literally much more red than green. It happens that this red is just slightly outside the range of the human eye.

Another important point is illustrated by the top pair of pictures in figure 13. The left member of the pair is an ordinary color picture. The right photo is an infrared color picture. You will notice than no detail is present in the shadow in the infrared image, while the steps of the building and the columns in front are visible in the ordinary color image. This phenomenon must be taken into consideration when using these films. The radiation

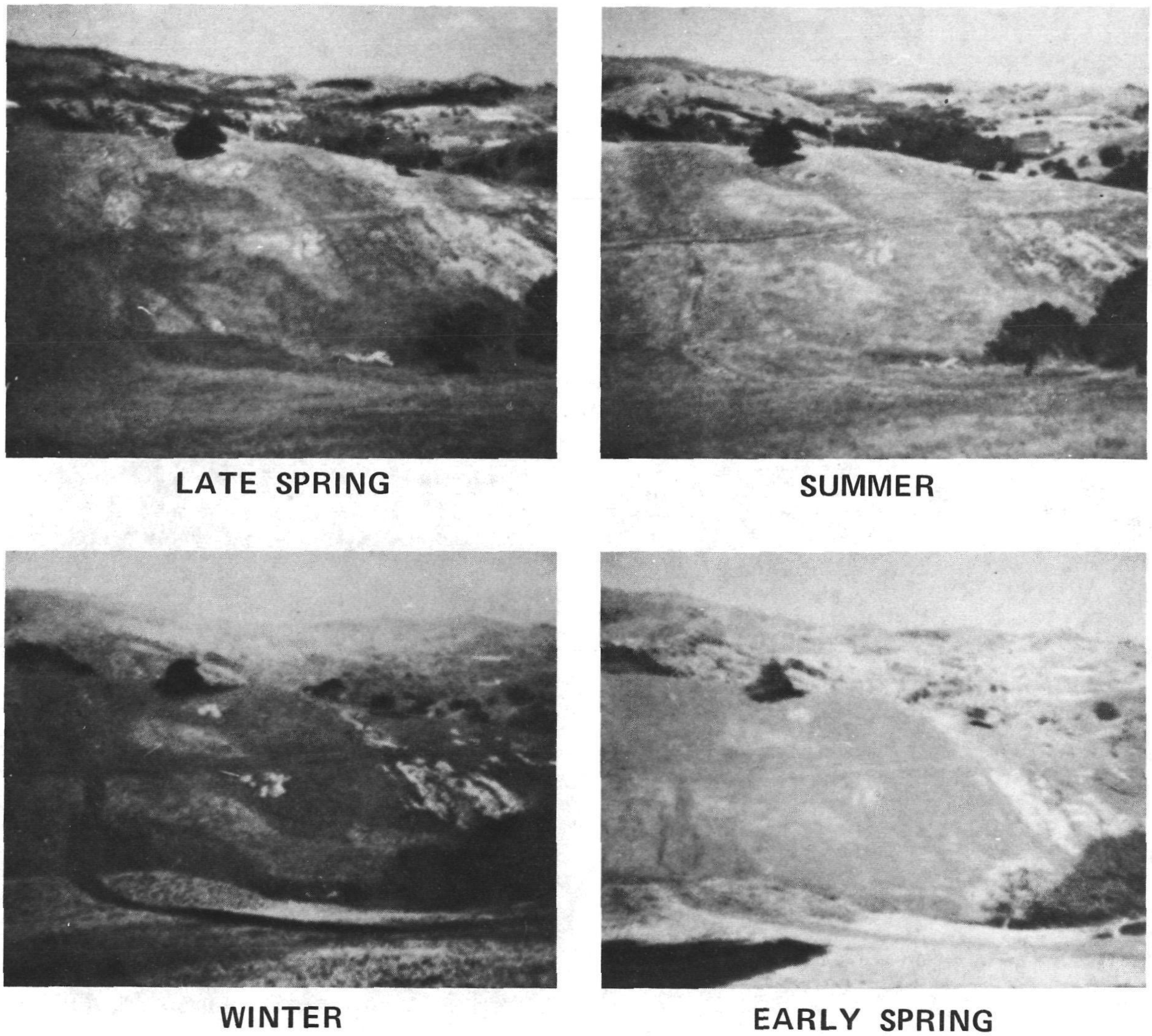


FIGURE 7. Aerial Ektachrome views showing seasonal states of a California range grass area. Order of decreasing suitability for mapping range conditions and estimating animal-supporting capacity: late spring, winter, summer, early spring.

is scattered, i.e., deviated from a straight-line path, much more at shorter wavelengths than at longer wavelengths. For that reason, if one wishes to see simultaneously in bright sunlight and in shadows, infrared Ektachrome is not an appropriate film, because illumination scattered around the corner at wavelengths to which it is sensitive is very small. This scattering is much higher in the blue band of ordinary color film.

One can record color information on color film; there is an alternative method of recording color information photographically. It we make three exposures of a colored scene, first through a red filter, then through a green filter, and then through a blue filter, we can record the color information on three frames of black-and-white film. By proper projection we can recover the color, as diagramed in figure 14. The upper part illustrates exposing black-and-white film selectively to blue, green, and red images. On developing the film, of course, we have black-and-white images. But we can project through each of those images with a light source corresponding to the color with which it was recorded and recover a color image. Figure 15 shows

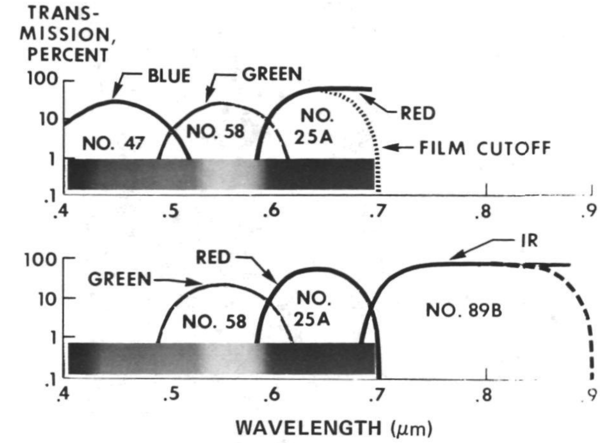


FIGURE 8. Color separation film bands using Kodak Wratten filters with ordinary color film (top) and with infrared Ektachrome film (bottom).

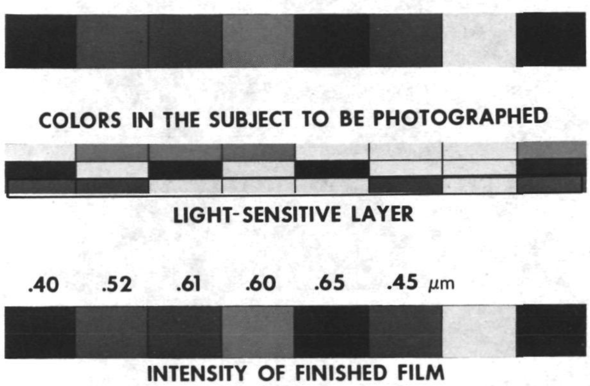


FIGURE 9. Spectral sensitivity of black-and-white film.

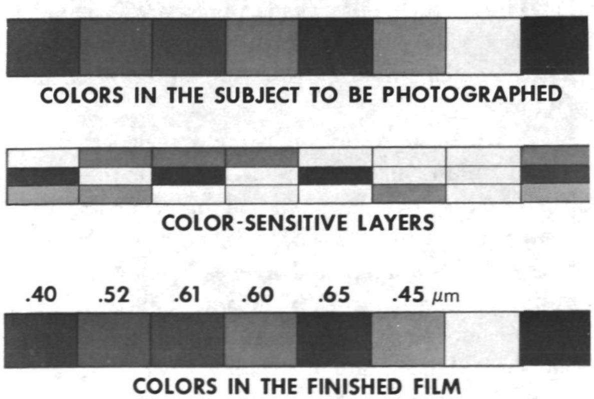


FIGURE 10. Spectral sensitivity of ordinary color film.

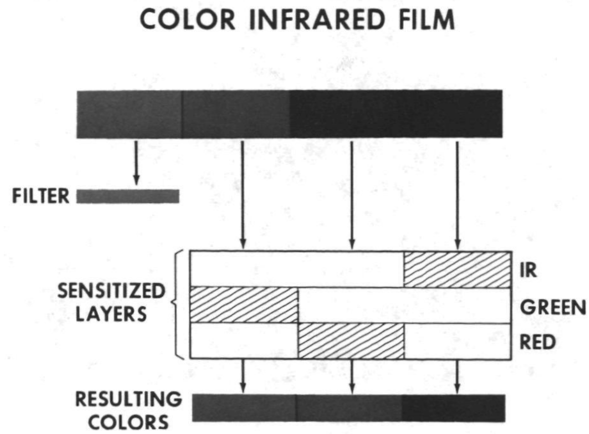


FIGURE 11. Spectral sensitivity of color infrared film.

very nearly the same process, but slightly different. This is the process used to produce "false color." The film images used are the same as in figure 14, but the projection process is different. It is possible to project the record of blue radiation with a red light, and so on, using a projection lamp of a different color than the filter used to record the image. Thus we recover an image that has a different distribution of color than we started with. That is essentially how we use infrared Ektachrome film.

Figures 16 and 17 illustrate the formation of ordinary color and infrared Ektachrome images from filtered black-and-white images. The upper row of figure 16 shows three images made through the filters of figure 8 which correspond to the sensitivities of the three emulsions of ordinary color film. In the lower row are three images exposed through the filters of figure 8 corresponding to the sensitivity regions of infrared Ektachrome film. By the reconstruction methods shown in figures 14 and 15, we can combine these images to obtain color images as shown in figure 17. The upper row shows both true and reconstructed ordinary color images, and the lower row shows true and reconstructed infrared Ektachrome images for comparison. This process is used with images from clusters of four Hasselblad cameras in the NASA aircraft. We do this because there is added control and flexibility in this method of obtaining color. Black-and-white films have greater latitude, being less critical with regard to exposure. We can more closely control the spectral region with filters than we can with the emulsions that come to us in the color film. For

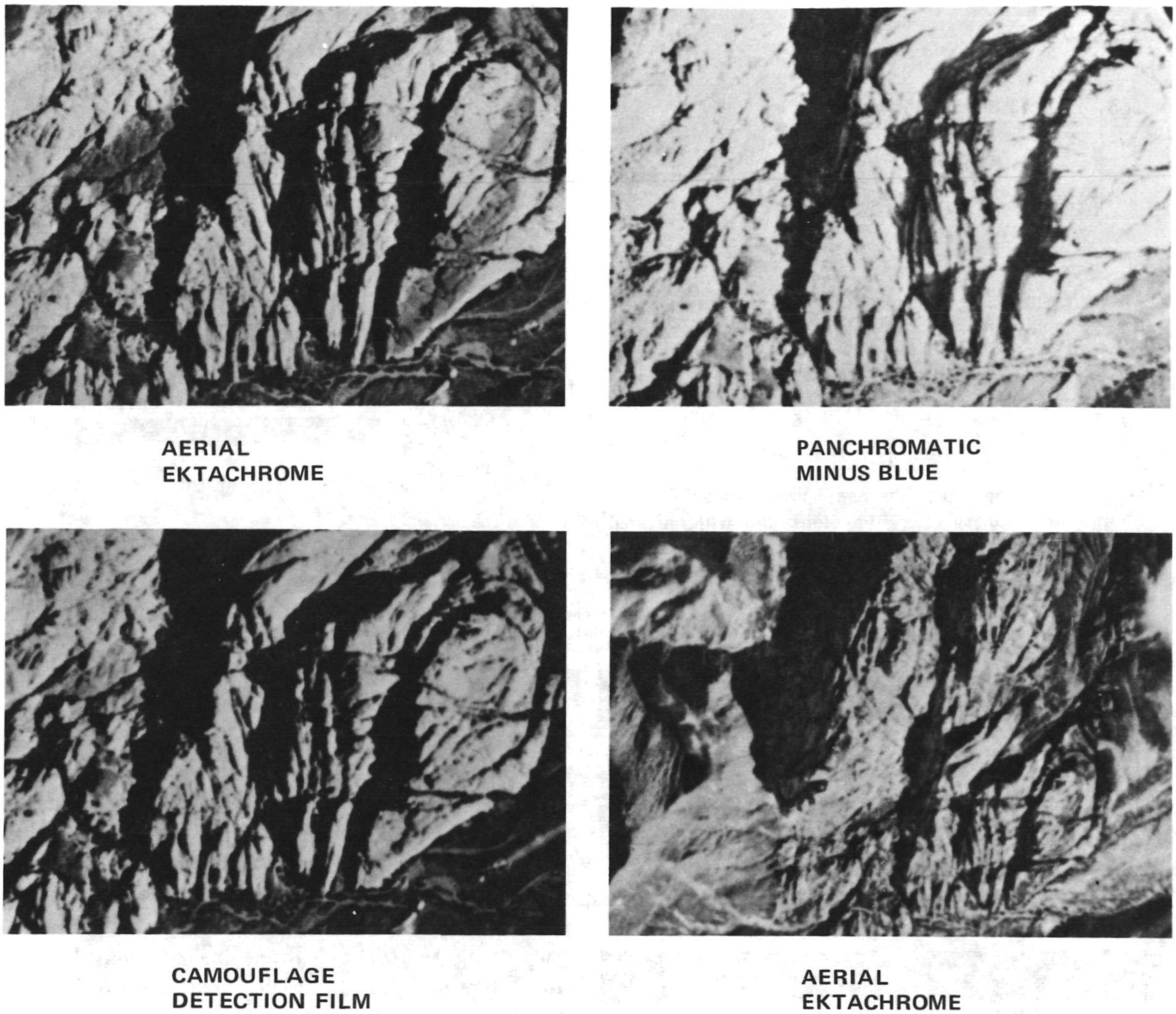


FIGURE 12. Film suitability for geologic interpretation.

some purposes, then, there are advantages in this more laborious method of recording color.

Figures 18 and 19 show another aspect of color discrimination. The chart in figure 18 shows the stages of growth of various plants. Cereal grains (wheat, for example) are green during some months and turn yellow and become ripe in other months. After the harvest in June, we see just the stubble. The bottom bar of the chart represents growing alfalfa, showing the periods when it is growing and cut. By observing these sequences of development for plants, we can construct what might be called a temporal signature, consisting of characteristic changes of behavior over a growing season. For the same region in the State of Arizona, figure 19 shows infrared Ektachrome pictures taken in March, April, May, and August 1969. One can notice a sequence of behavior for each field over those months which agrees with the crop calendar (figure 18).

We can also record in many wavelength bands with scanning instruments as shown in figure 20. Figure 21 shows the operation of an airborne IR scanning instrument. There is always a rotating mirror for scanning and a telescope to focus the radiation on a detector. This is a single-wavelength instrument. Normally the signals are tape-recorded and then played back to a cathode ray tube, whose display is in turn recorded on a strip of film.

Figure 22 illustrates a multispectral version of a

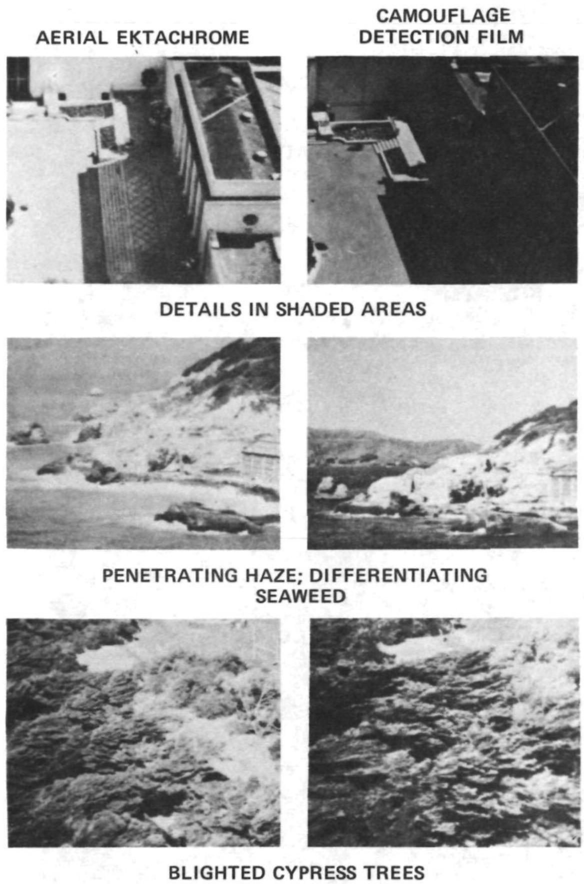


FIGURE 13. Comparison of film types for different applications.

scanning instrument. It uses the same rotating mirror and focusing telescope. In place of the single-band detector there is a prism or a grating which separates the radiation by wavelength. A separate detector can be placed where the ultraviolet is, and perhaps several different detectors in the blue, green, red, and infrared portions. Radiation from many wavelength bands can thus be recorded simultaneously and in complete synchronization.

Figure 23 is a diagram of how we use the information from such a system. On the left is the region being observed. Data observed and recorded with the multispectral instrument is placed in a computer for processing. Data from many channels must be in complete synchronization so that the computer can compare the distribution of radiation across the many wavelength bands with known standards, producing a picture in which the material type is indicated by color. This is a multispectral sensing and interpretation or processing system.

Figure 24 shows the pictures we can get without processing, since they are recorded in many channels of one instrument. We have an ordinary color photograph, an ordinary infrared Ektachrome photograph, and an ordinary panchromatic film for comparison. Below are 18 very narrow-band images. Figure 25 shows a second such set of images. These differences provide experimental verification that each material exhibits a characteristic change in behavior across all of these bands. This characteristic variation in behavior can be used for identification.

Figure 26 is an ordinary panchromatic mosaic of many prints made with black-and-white conventional panchromatic film from an agricultural area containing rice at one stage of growth, rice in other fields at another stage of growth, safflower plants, and bare earth. Since there is not much contrast in the picture, it would not be possible to identify the materials from the information present.

Figure 27 shows 18 observations of the same area with a multispectral instrument. Since there are many differences in the appearances of the fields, there are characteristic patterns which can be used in a spectral recognition system. It is apparent that recognition identification based upon the pattern of reflectivity over these 18 bands is not a process for which the human brain alone is well suited.

The information in these many bands can be processed and displayed in many different ways. For example, figure 28 represents a reconstruction of an image that could be obtained with panchromatic film, but it is made from data in the multispectral scanner using information from small filters. The three spiked response curves indicate the bandwidths of the filters used. If we add data from channels represented by those three filters, we can obtain the same results we get from panchromatic film.

Figure 29 shows a reconstruction of the type of image obtained with black-and-white infrared aerographic film. It is an image of the radiation from the band indicated, and it is equivalent to the image we would get using infrared aerographic film in a camera.

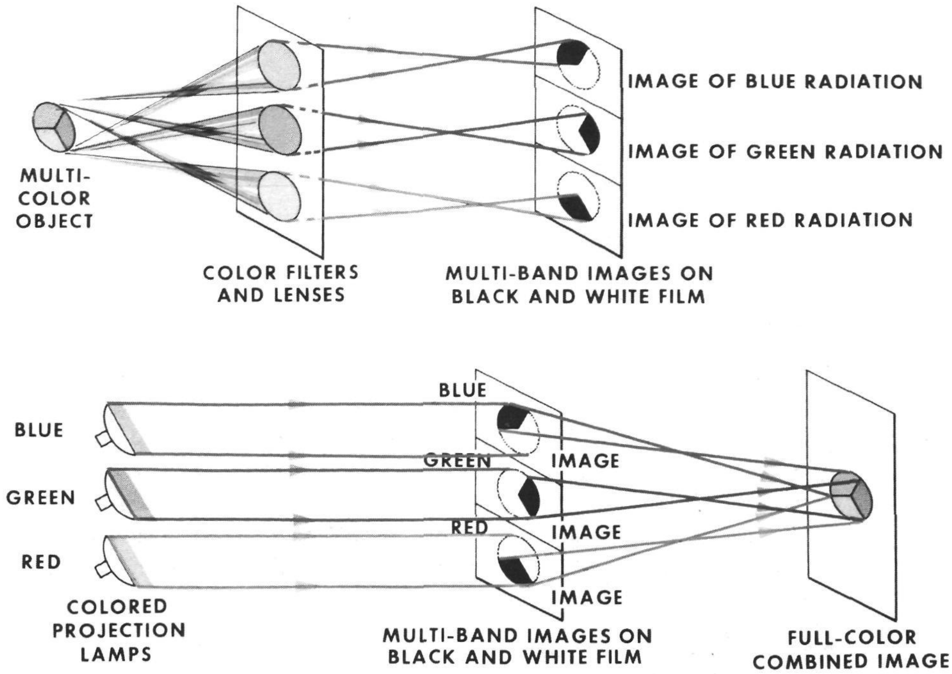


FIGURE 14. Schematic diagrams of multiband camera operation (top) and multiband color reconstruction viewer (bottom).

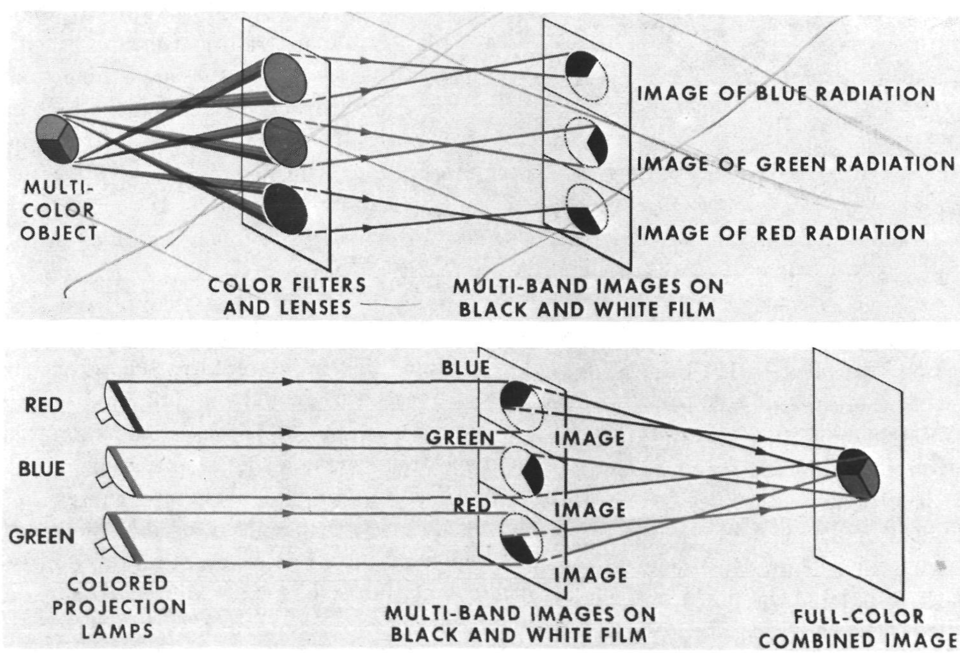


FIGURE 15. False color reconstruction.

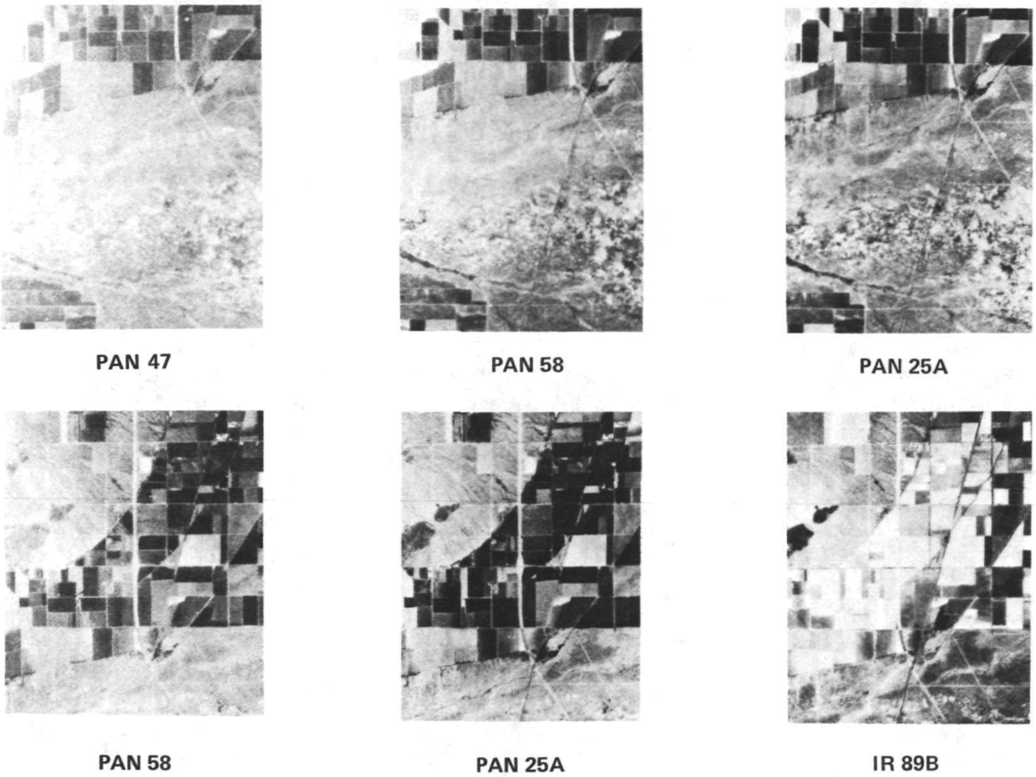


FIGURE 17. Examples of color reconstitution. Color images B, C, E, and F were made from multiband photos. Images A and D are single-band photos taken over the Phoenix (Arizona) test area at approximately the same time.

Figure 30 was constructed by taking the data from the channels indicated and adding them together with suitable dyes and constructing the color film. Figure 31 is the same type of reconstruction for infrared Ektachrome film, made by assigning blue dyes to radiation in the green band, green dyes to the red band, and red dyes to the infrared radiation. Each of the three dyes in the image can be assigned to some wavelength in the recorded radiation. With 18 bands of information and three colors, there are more than 100 000 possible combinations.

Figure 32 is a picture with one ultraviolet band, to which we have assigned the blue dye, and two visible bands. Notice that the two safflower fields are different in appearance. That difference is important in this case. These two fields contain the same crop at the same stage of growth. They appear different here because there exists a difference which can be seen only in the ultraviolet. Referring to figure 27, you can see that those two fields have quite different densities in the ultraviolet, while no other band exhibits such a strong difference. Many people believe that in the ultraviolet there is no information that does not appear in the blue part of the visible. Here is one example in which there is obviously information in the ultraviolet that does not appear elsewhere in the optical spectrum.

Figure 33 shows the way the world would appear if you had infrared eyes. Here we have three infrared bands which have been assigned three different colors. For the first time, two fields of young rice at the bottom right look different. I will explain later why that is so.

Figure 34 is a picture with ultraviolet, visible, and infrared information. Here we see, again because we have the ultraviolet information, two safflower fields different in appearance. That is the first of three uses of color that I will discuss. In this use, we have assigned the color of the dye to a wavelength of incoming radiation. Figure 35 shows a different aspect of the radiation. Since the information is processed to show only lines where the

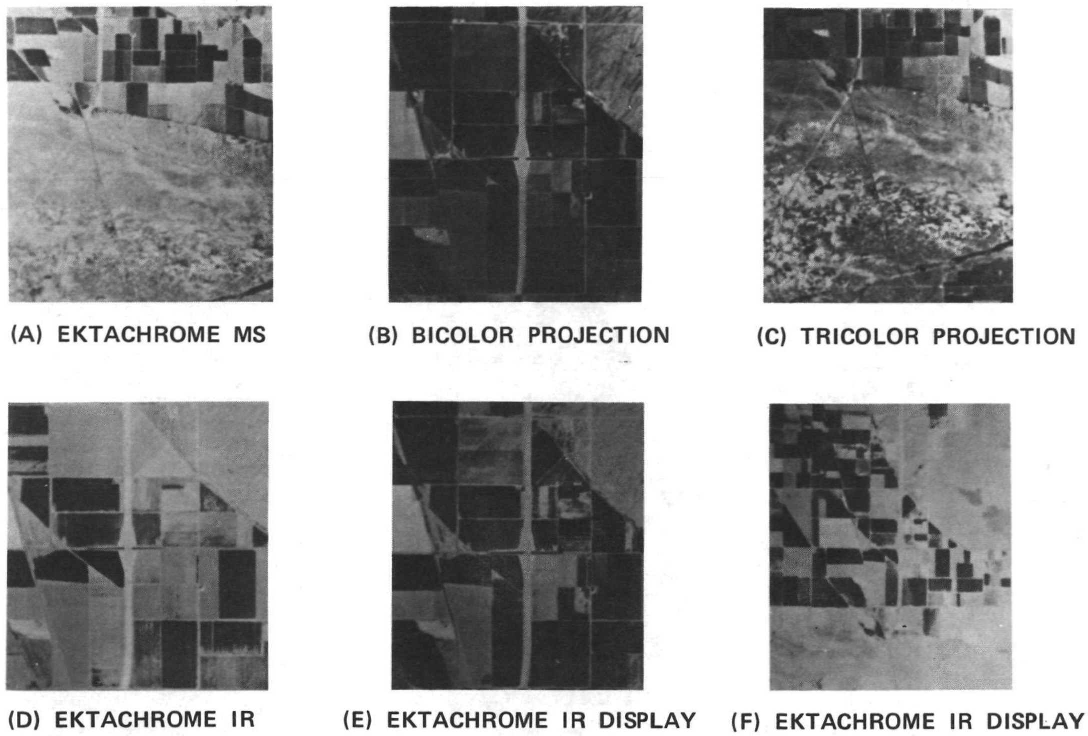


FIGURE 16. Multiband photography of Phoenix test area. The three photos in each row were used to reconstitute a color IR display.

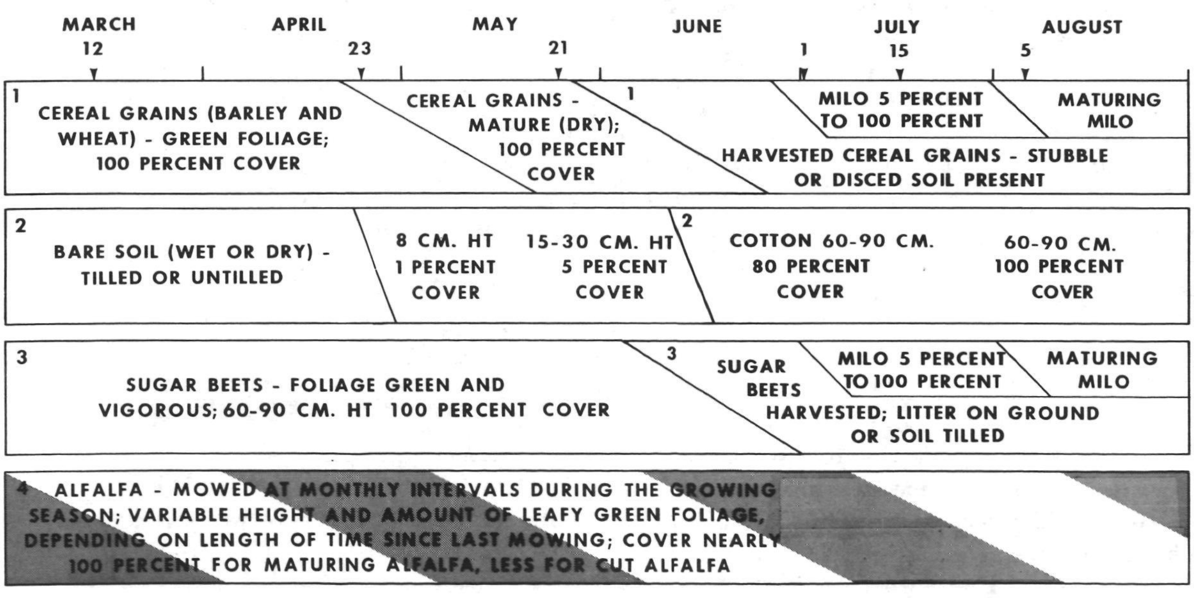
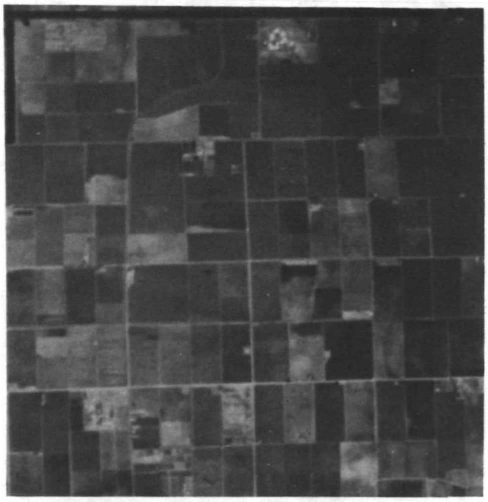
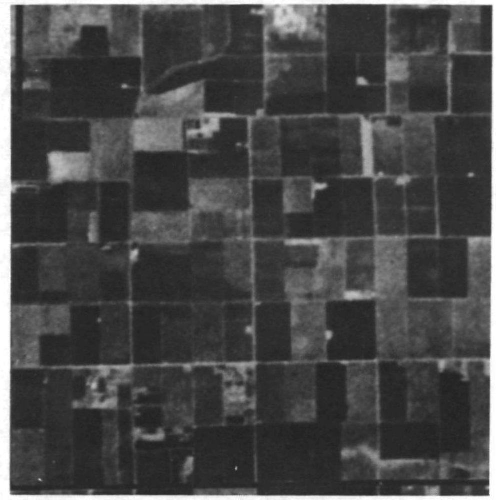


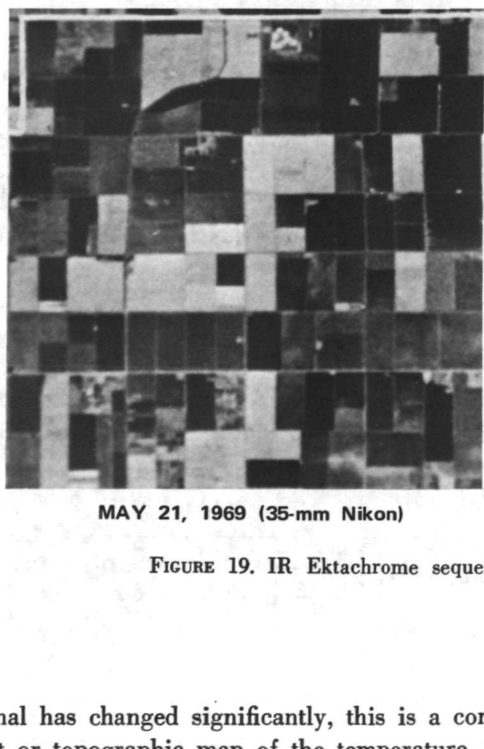
FIGURE 18. Crop calendar for Mesa (Arizona) test site (1969).



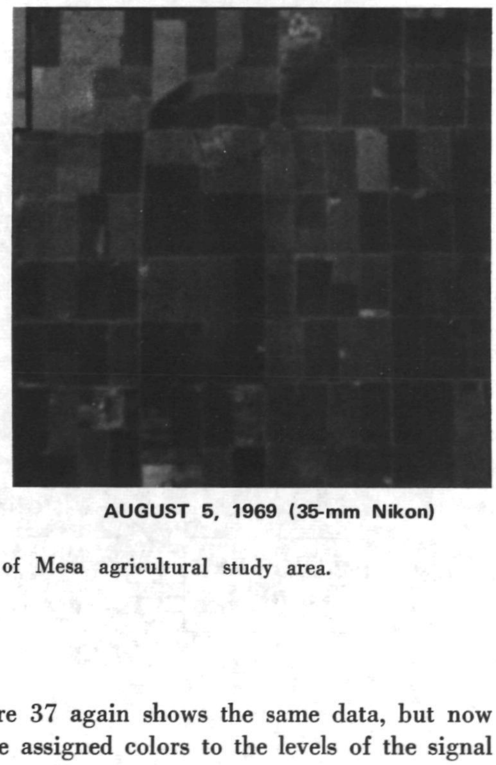
MARCH 12, 1969 (70-mm Hasselblad)



APRIL 23, 1969 (35-mm Nikon)



MAY 21, 1969 (35-mm Nikon)



AUGUST 5, 1969 (35-mm Nikon)

FIGURE 19. IR Ektachrome sequential photography of Mesa agricultural study area.

signal has changed significantly, this is a contour plot or topographic map of the temperature. That is only one of several ways of presenting the information. A more useful method, for many purposes, is illustrated in figure 36, which shows the same data but with a density assigned to each level of temperature. Here again we see that the field of young rice at lower right is different from the neighboring rice field just above it.

Figure 37 again shows the same data, but now we have assigned colors to the levels of the signal in that band. Once more, the two fields of young rice at lower right appear quite different. The reason for the difference is that water was drained from the lower field but not from the upper field. The dry field in sunlight attained a much higher temperature —in fact, very nearly the same temperature as a field with no vegetation at all. This is the second

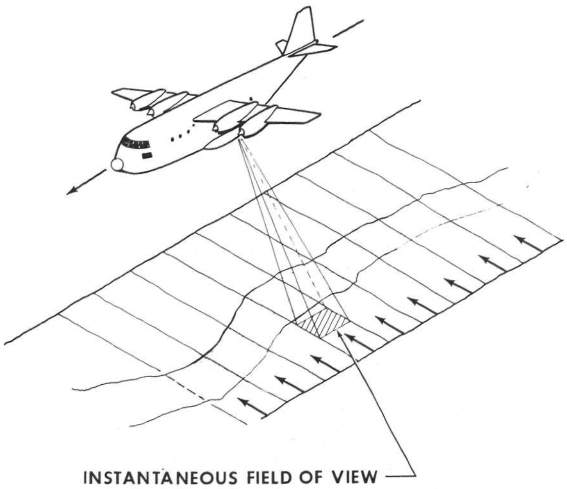


FIGURE 20. Scan pattern for a typical scanner.

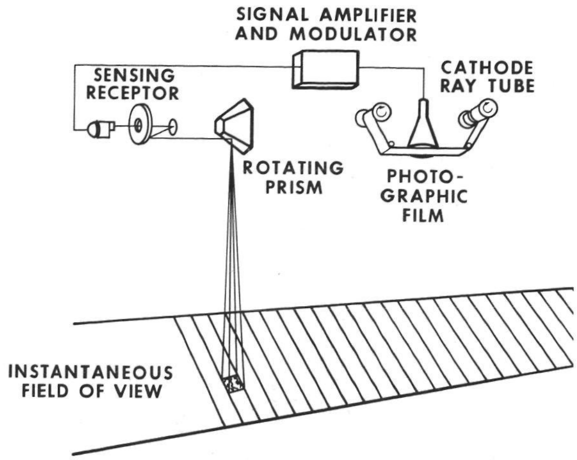


FIGURE 21. Schematic diagram of IR scanner.

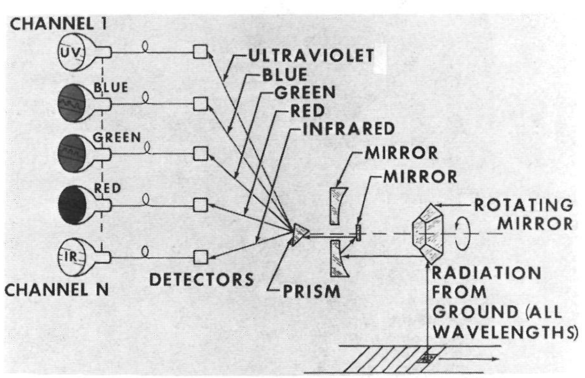


FIGURE 22. Schematic diagram of multispectral scanner.

use of color: The color has been assigned now not to the wavelength, but to the magnitude or level of the signal.

Figure 38 shows temperatures measured with thermocouples for a number of common materials. These measurements recorded for one complete daily cycle, were made near Ann Arbor, Michigan by scientists at the Willow Run Laboratories of the University of Michigan. It is apparent that each material exhibits a characteristic pattern of temperature behavior.

Figure 39 shows the radiation spectra for two safflower fields and two rice fields, plotted from the data in figure 27. For the two safflower fields, the green one differs significantly from the black one

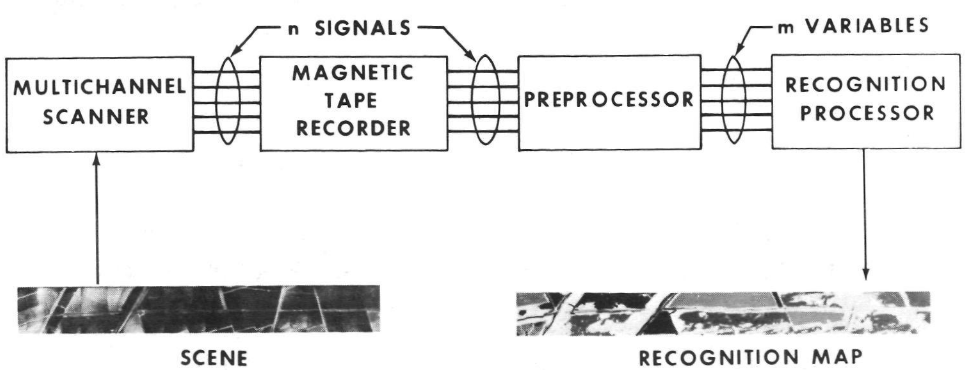


FIGURE 23. Diagram of multispectral remote sensing and processing system.

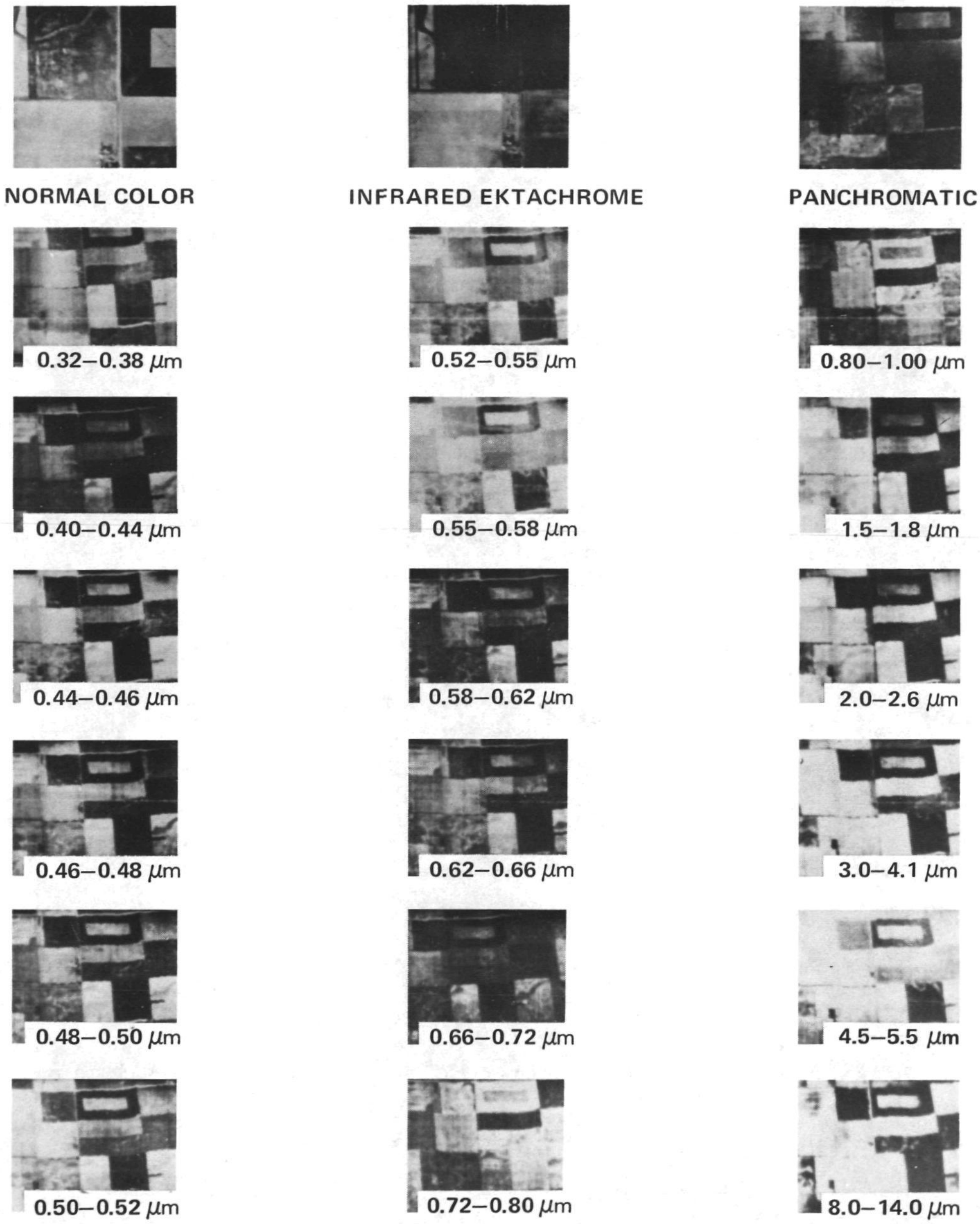


FIGURE 24. Comparison of imagery and photography for area 1 (University of Michigan).

only in the ultraviolet. Thus, if we had proper ultraviolet information, we could distinguish between them.

The plots of the rice fields are nearly the same until we get to infrared wavelengths, and there the one plotted in red differs from the one plotted in blue. For each field, at some place in this spectrum, there are strong differences, and that is why we can use a computer to recognize materials. Figure 40 shows the result of having a computer use that spectral information to print first only the 20-cm-tall rice and secondly the 10-cm rice (this is a very sensitive process because it can differentiate two stages of growth of the same plant). Next, the computer was asked to present a picture of the safflower, and then a picture only of the bare earth.

FIGURE 25. Comparison of imagery and photography for area 2 (University of Michigan).

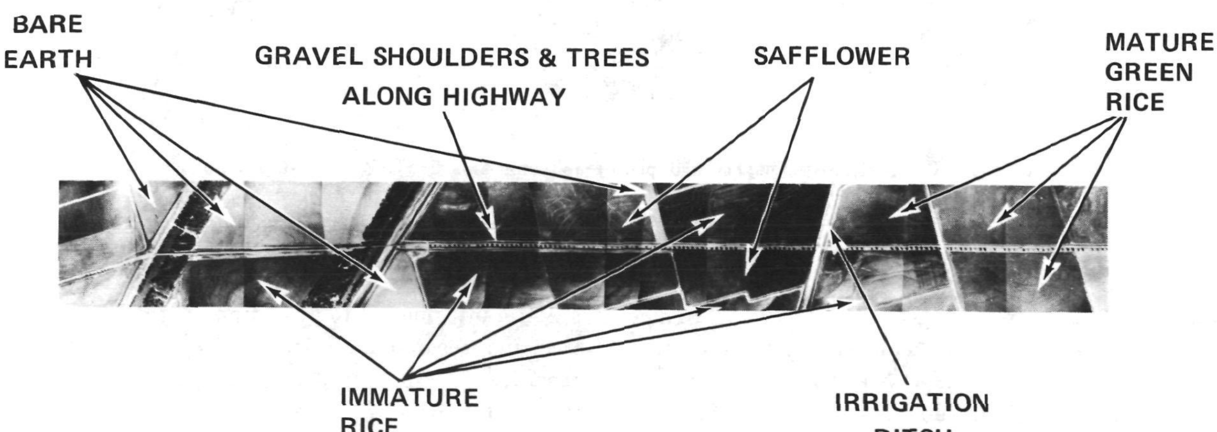


FIGURE 26. Panchromatic photomosaic of Davis (California) agricultural area.

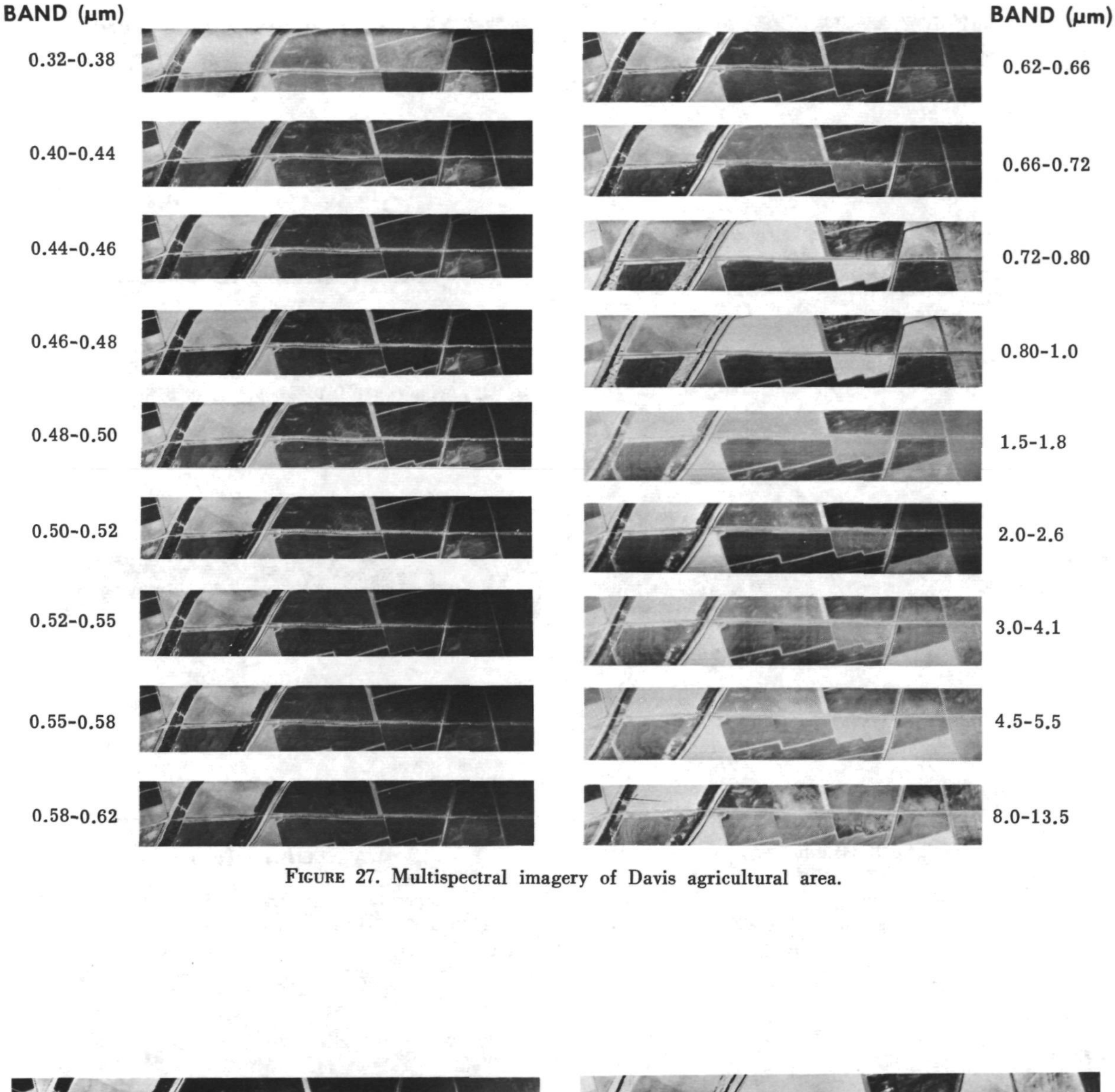


FIGURE 27. Multispectral imagery of Davis agricultural area.

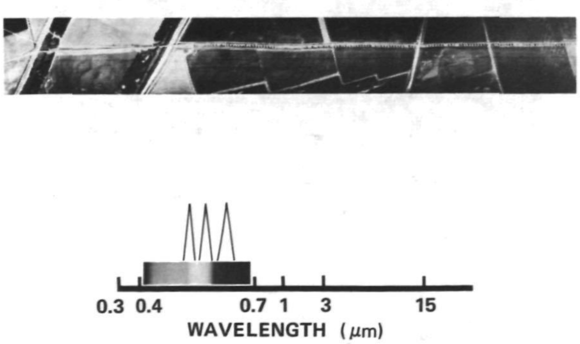


FIGURE 28. Response of simulated panchromatic film with K2 yellow filter (blue, 0.52 to 0.55 μm; green, 0.55 to 0.58 μm; red, 0.58 to 0.62 μm).

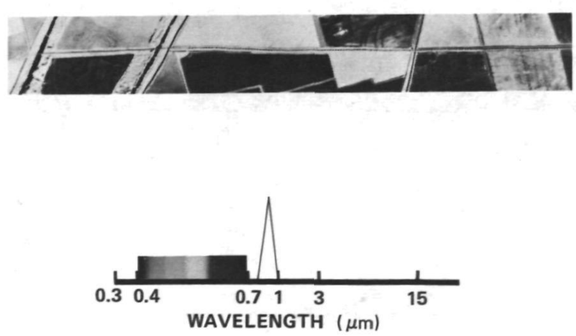


FIGURE 29. Response of simulated IR aerographic film (positive transparency, 0.8 to 1.0 μm).

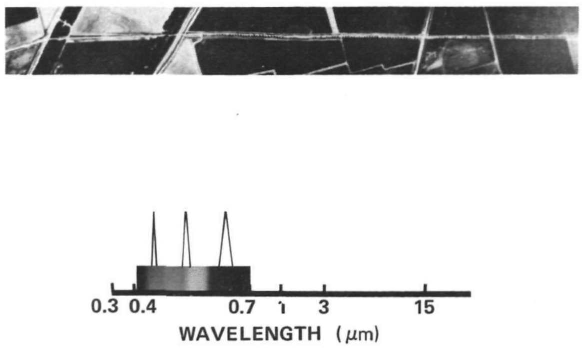


FIGURE 30. Response of simulated color film (blue, 0.44 to 0.46 μm; green, 0.52 to 0.55 μm; red, 0.62 to 0.66 μm).

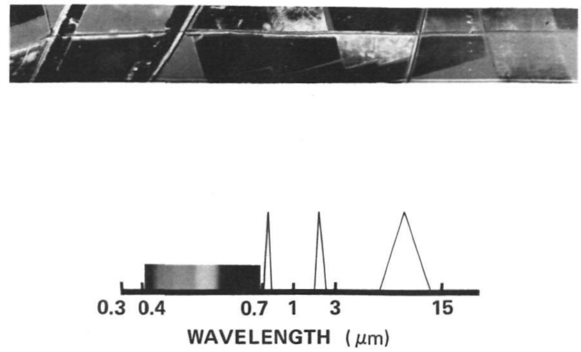


FIGURE 33. Color wavelength translation in IR (blue, 0.72 to 0.8 μm; green, 2.0 to 2.6 μm; red, 8 to 14 μm).

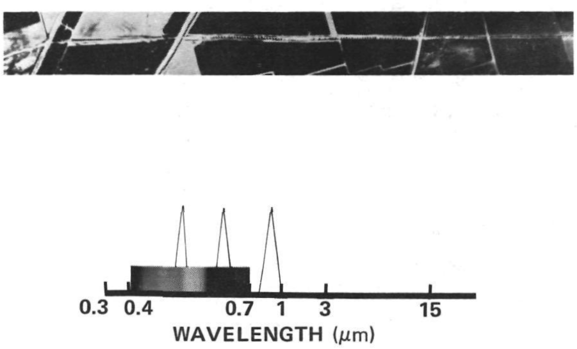


FIGURE 31. Response of simulated IR Ektachrome film (blue, 0.52 to 0.55 μm; green, 0.62 to 0.66 μm; red, 0.8 to 1.0 μm).

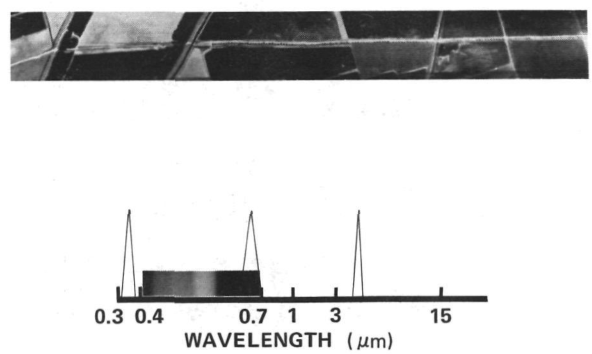


FIGURE 34. Color wavelength translation in UV, visible, IR (blue, 0.32 to 0.38 μm; green, 0.66 to 0.72 μm; red, 4.5 to 5.5 μm).

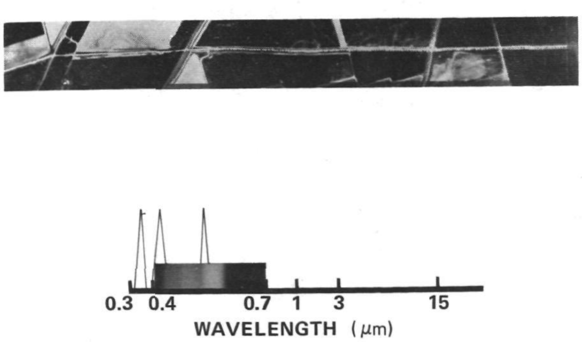


FIGURE 32. Color wavelength translation in UV, visible (blue, 0.32 to 0.38 μm; green, 0.40 to 0.44 μm; red, 0.52 to 0.55 μm).

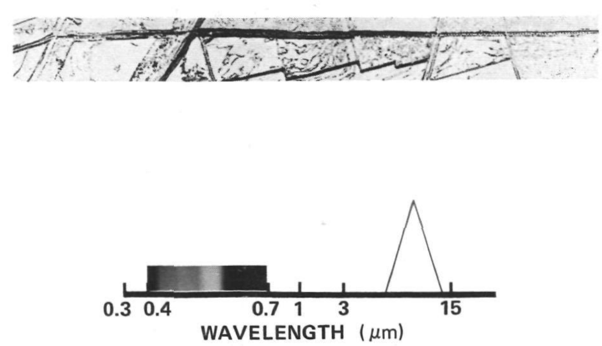


FIGURE 35. Thermal contours in far IR (8 to 14 μm).

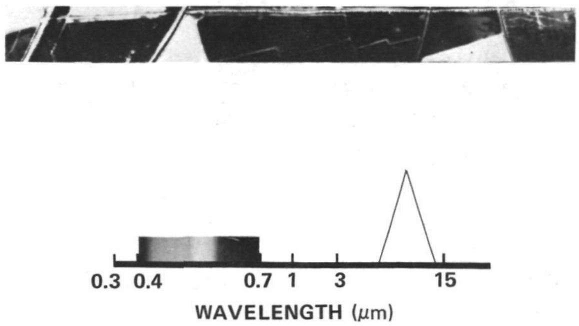


FIGURE 36. Quantized video picture (8 to 14 μm).

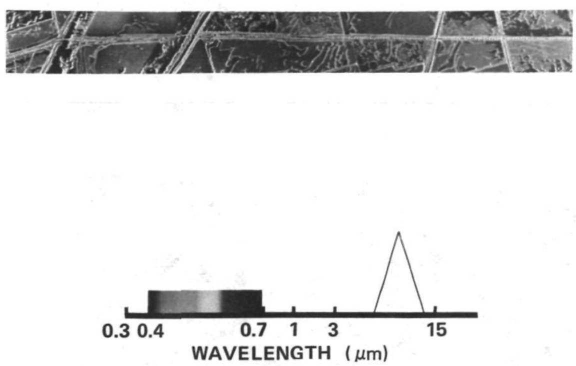


FIGURE 37. Color coding of apparent temperatures (8 to 14 μm). Highest temperature is violet, decreasing through blue, green, yellow, orange, red, brown, to black (lowest).

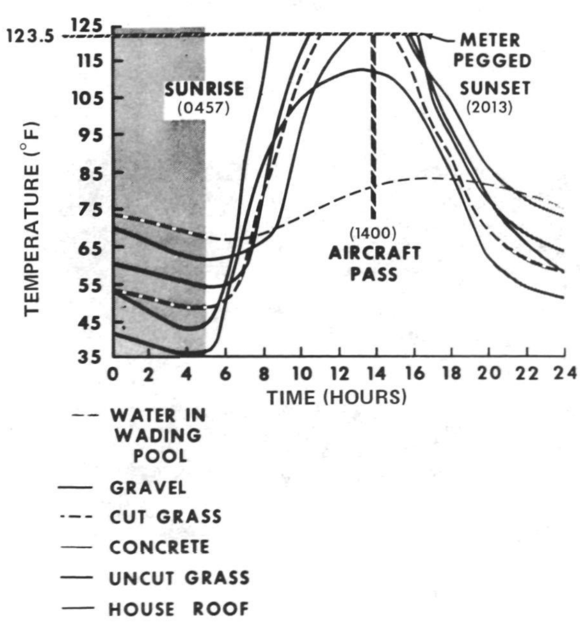


FIGURE 38. Plot of temperature vs time for selected surfaces (Coles Farm, 25 June 1963).

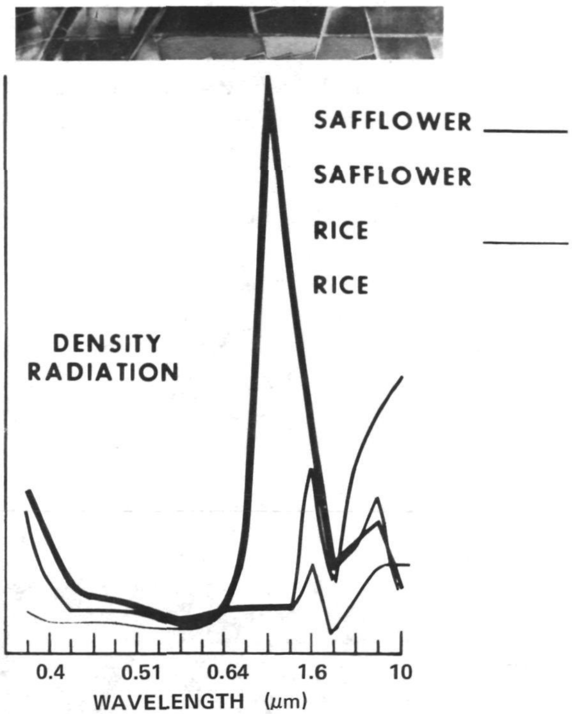


FIGURE 39. Sampled spectra of vegetation in Davis agricultural area.

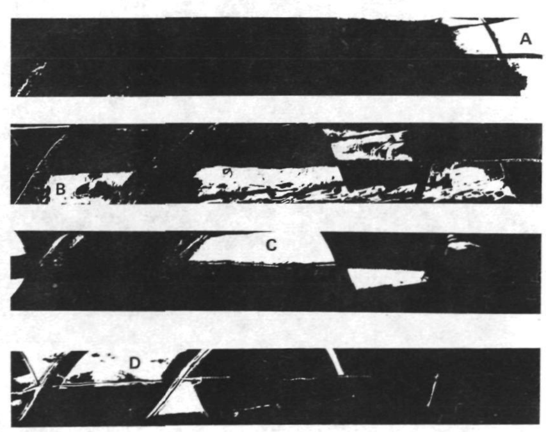


FIGURE 40. Recognition pictures for Davis agricultural area. White areas represent (A) mature green rice (0.46 to 0.48 and 0.58 to 0.62 μm); (B) immature rice (0.48 to 0.5 and 0.62 to 0.66 μm); (C) safflower (0.72 to 0.8 and 0.8 to 1 μm); and (D) bare soil (0.46 to 0.48 and 0.62 to 0.66 μm).

Figure 41 is a plot of the signal through two fields at the left of the picture in several wavelength bands. One field is immature rice and the other is bare earth. On the left, you can see that the signal levels for fields A and B are the same; but on the right, they are different. This is just another method of portraying the difference between the two signals.

Figure 42 shows the same information as that in figure 41, but we have indicated the nature of the material by color. The colors correspond to an identification of the materials by the computer.

Figure 43 shows the result of work done by a digital computer. Organizations such as the statistical reporting service of the Department of Agriculture normally do not wish to look at pictures; they are interested in tabular information. If the computer can recognize the nature of the material, it is a simple task to ask the computer to take the process one step further and add areas.

I hope I have given you some concept of the degree of success we are beginning to achieve in remote sensing. Very soon now, the Earth Resources Technology Satellite and the Skylab Satellite will have multispectral sensor systems in orbit. The observation system will give us information regarding the situation at the instant of observation. The main value of these systems will be in predicting future events. To make such predictions, we need models of the environment in which to insert the observation data.

Figure 44 shows the nature of the sensing acti-

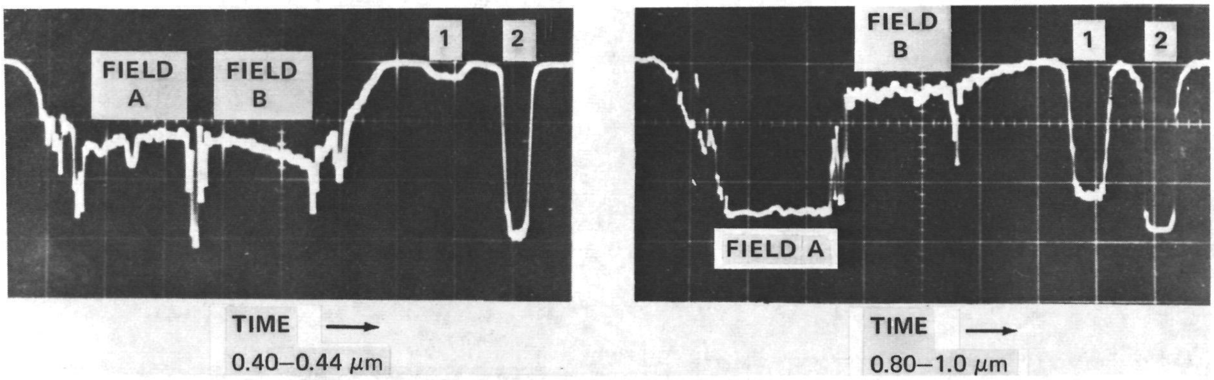


FIGURE 41. Typical spectrometer video data (California rice fields). Numerals 1 and 2 indicate calibration lights.

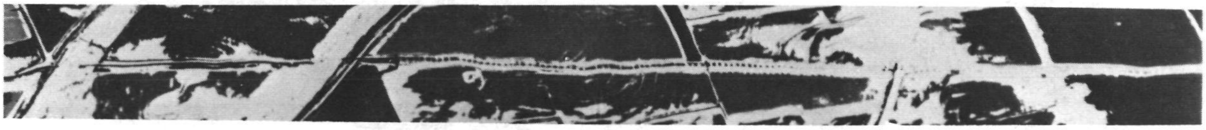


FIGURE 42. Recognition picture of Davis agricultural area (red, relatively mature green rice; blue, immature rice; green, safflower; black, bare earth).

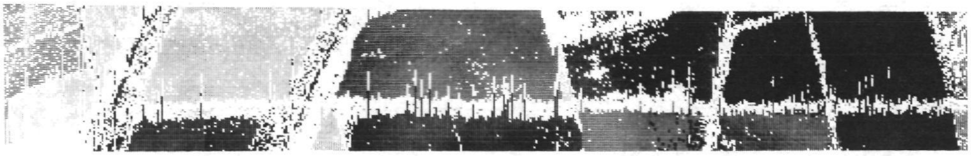


FIGURE 43. Digital recognition map of Davis agricultural area.

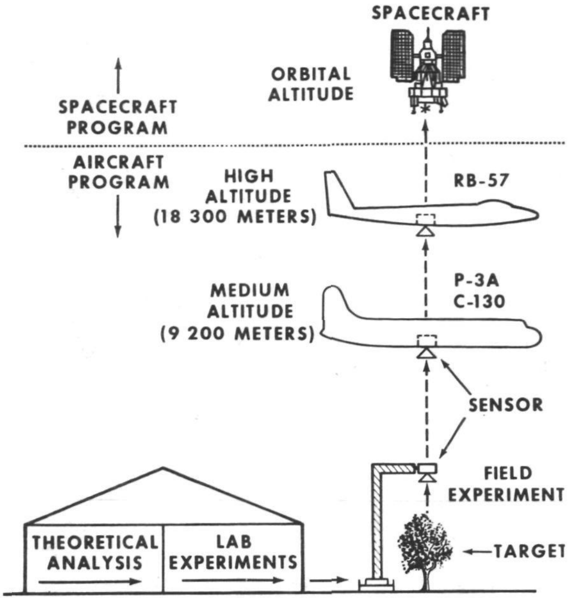


FIGURE 44. Development of remote sensing techniques.

vities in which we must be engaged in the future. As we get spacecraft in orbit, we must not fail to do certain things on the ground to support them, such as the theoretical analyses that will provide the understanding. We are dealing with a large system of many parts, and our research work must contain elements of many kinds of activity.

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Remote Sensing and Time-Variant Phenomena

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Geographic Applications Program
U.S. Geological Survey

Remote sensors carried on aircraft and satellites have shown considerable promise for gathering data on environmental change at and near the Earth's surface. Ranging from worldwide measurements of the atmosphere, oceans, and ice caps, to observations of changes in the land, water, and air resources at regional and local scales, the studies of environmental change are discussed in the context of their relationship to both cyclic (periodic) and evolutionary (developmental) processes at work in the environment. An example illustrates ways that remote sensing monitoring systems might be incorporated into operational information systems for keeping track of changes that take place in the course of regional or national economic development.

Repeated observations of the Earth's surface are now possible and in fact are being made at this moment by the weather satellites. By comparing the change between yesterday's and today's cloud pictures, the meteorologist can gage the speed and direction of approaching storm systems, and thus give us a better prediction of tomorrow's weather.

Within the context of the Earth resources surveys that are the subject of this workshop, I invite you to share with me some thoughts on the subject of change—how it occurs at various scales over the surface of the Earth, what it means in terms of remote sensing observations, and how the Earth resources specialists might in fact follow in the footsteps of the meteorologists and develop remote sensing systems to observe trends and predict the supplies of usable land, water, and other important Earth resource quantities.

Let us first look at some examples of kinds of environmental changes that can be observed by remote sensors, at various scales of observation ranging from worldwide to the individual landholding. Then we shall discuss the importance of understanding the environmental processes that bring about the changes. Finally, a practical example from the field of regional economic development will be presented, illustrating ways that airborne and spaceborne remote sensors might be incorporated into an operational system for monitoring national or regional environmental change.

REMOTE SENSING OBSERVATIONS OF ENVIRONMENTAL CHANGE

In examining the environmental phenomena from the viewpoint of changes which are significant to Earth resources surveys, we are first struck by the great variety of those phenomena and the great range in scales of observation required to keep track of them. One way to approach the application of remote sensors to the observation of these changes is to examine the problem on the basis of the geographic scale, ranging from worldwide down to the individual landholding, which encompasses the phenomena of interest. Some examples of phenomena arranged in this way are listed in table 1.

At the continental or worldwide scale are certain phenomena relating primarily to atmospheric and oceanic dynamics which transcend national boundaries and require essentially a planet-wide data-gathering network to be effective. Observations from these networks are likely to be of interest to resource managers and planners in all nations.

For example, information on the movements of clouds and storm systems, so vital to weather fore-

Table 1. Remote sensing observations of environmental change

Scale	Phenomena	Remote sensor	Time period
Continental or worldwide	Cloud systems	Camera, scanner	Daily
	Air temperature & moisture	Radiometer, spectrometer	Hourly, daily
	Dust	Camera, radiometer	Daily, seasonally
	Ocean temperature	Radiometer	Daily
	Ocean color	Camera, scanner, spectrometer	Daily, seasonally
	Ice	Camera, microwave	Seasonally, annually
Nation or region	Air pollution	Camera, spectrometer	Daily, seasonally
	Floods	Camera, radar	Seasonally
	Lakes and reservoirs	Camera, scanner	Daily, seasonally
	Albedo	Scanner	Seasonally, annually
	Natural vegetation	Camera, scanner	Seasonally
	Crops	Camera, scanner	Seasonally
	Clearings	Camera, scanner	Monthly
	Soils	Camera, scanner	Seasonally, annually
	Land use	Camera, scanner, radar	Annually
	Landslides	Camera, radar	Irregularly
	Geologic structure	Camera, radar	Indefinite
City	Air pollution	Camera, spectrometer	Daily
	Land use	Camera, radar	Semiannually
	Transport facilities, vehicles	Camera, radar	Daily
	Water quality	Scanner, radiometer	Daily
Landholding	Crop vigor	Scanner, camera	Seasonally
	Erosion	Camera, radar	Seasonally
	Woodland	Camera	Seasonally
	Environmental hazard	Camera, scanner, radar	Irregularly

casting, is now being obtained routinely from weather satellites. (See figure 1.) Cameras and scanners operating in the visible portion of the spectrum obtain daytime data on cloud patterns, and infrared scanners obtain similar nighttime data. As indicated in table 1, the time period required for repeating the observation, so that useful monitoring and prediction can be done, is approximately a day, although slightly less frequent cloud observations may be sufficient for tracking major storms over the oceans, and slightly more frequent observations may be required if smaller features such as thunderstorms are to be monitored.

At this point a major gap in the discussion, as well as in table 1, should be pointed out. The monitoring of cloud patterns is the only item of change assessment under discussion which is actually operational from satellite systems at the present time. By "operational" is meant the employment of the satellite sensor system by an authorized agency or organization, on a routine basis, for use in fulfilling one of the organization's official functions. Thus, the meteorological services in a number of countries are obtaining and using cloud data from the weather satellites in preparing their analyses and forecasts.

All of the other phenomena discussed here in terms of remote sensing observation of change are under investigation to determine feasibility, or have been demonstrated to be possible for operational change assessment using sensors carried in

FIGURE 1. ATS view of Earth.

aircraft. The question of monitoring changes in Earth resources on an operational basis using large-scale satellite systems will be determined in part by the responses of people who have resource planning and managing responsibilities, such as those who are attending this workshop. As will be mentioned later, decisions of this nature will have to be made in light of regional and national program priorities for data, carefully balanced against cost considerations.

With the above qualifications in mind, let us proceed to examine the prospects for setting up future remote sensing observation systems for systematically monitoring time-variant phenomena. Worldwide measures of air temperature and moisture, by combinations of radiometric and spectrometric techniques, now seem operationally feasible. Such instruments could be carried on either aircraft or satellites, but satellite measurements would be preferable, giving a profile through the entire atmosphere and wide spatial coverage. The critical time periods for such measurements would be hourly or daily.

Dust and other solid particles that are being carried great distances by atmospheric motion can often be observed by cameras and radiometric sensors, even from satellite altitudes. Observations of dust distribution and movements, repeated at daily or seasonal intervals, would be valuable for climatological studies or for estimating the effects on the atmosphere of various land use practices.

In similar fashion to the making of atmospheric measurements, worldwide assessments of ocean temperatures and suspended matter could yield valuable information on the movement of currents and the changing distrubution of nutrients in fishing grounds. The concentrations of algae or dissolved solids may be reflected in ocean color, as determined by various combinations of cameras, scanners, and spectrometers. Ice is another phenomenon whose changing distribution is important to a number of countries. In clear daytime weather ice distributions can be easily determined by camera observations. However, because much of the area of interest for ice observations is likely to be cloudy or in long polar nights, an all-weather day-or-night observation system using radar or microwave sensors would be more reliable in obtaining, for example, information on the condition of shipping lanes. Also, systematic monitoring of the extent of glaciers, especially the Greenland and Antarctic ice caps, would be valuable in assessing prospects for changes in climates or sea level.

The remaining portions of table 1 indicate examples of a variety of phenomena which are important in Earth resources surveys at national, regional, urban, or individual landholding levels of operation. Further discussions of ways that the remote sensing observations can be incorporated into programs for monitoring environmental change are contained in the following sections on environmental processes and the monitoring of regional development. Figure 2 shows the locations of the pilot projects from which imagery examples were obtained. Figures 3 thru 8 illustrate the various scales of remote sensor imagery used to indicate change.

ENVIRONMENTAL PROCESSES

The phenomena listed in table 1 are only a few of many which may be important elements in a remote sensing observation system for keeping track of environmental change and monitoring the changing status of a nation's vital Earth resources. Also, environmental monitoring could involve tremendously large amounts of information, owing to the large areas covered, the level of detail required

FIGURE 2. Pilot projects: urban and regional change detection.

FIGURE 3. Nimbus view of central Atlantic States region.

for some observations, and the need for frequently repeating many of the observations of rapidly changing phenomena. Therefore, in developing any regional, national, or international system for monitoring changes on the surface of the Earth, a carefully devised strategy is necessary to assure the actual need and the optimum use of data that are to be collected.

Foremost in such a strategy should be a consideration of the environmental processes which produce the changes we want to monitor. Several categories of these environmental processes are listed in table 2. Knowledge of these processes and their effects has been built up through years of painstaking research by scientists who specialize in the various disciplines and, more recently, by interdisciplinary teams who study the combined effects of the various processes and how they interact with each other. Improved knowledge of the environmental processes and how they operate in a particular region will result in improved ability to

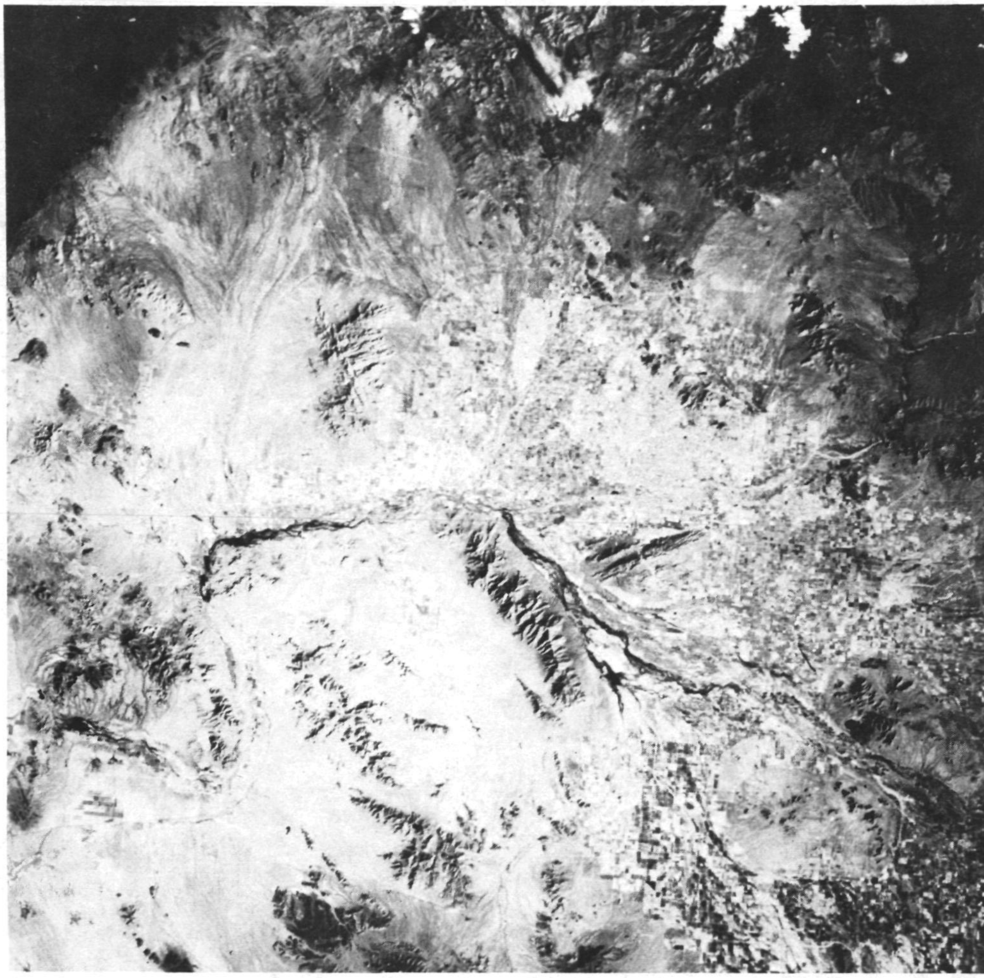

FIGURE 4. Apollo 9 color IR photo of Phoenix and vicinity.

schedule remote sensing observations for environmental monitoring (figure 9).

For example, these environmental processes might be grouped for convenience into two categories: cyclic (or periodic), and evolutionary (or developmental). Cyclic processes are those that operate at regular (or perhaps irregular) intervals, with the environmental condition (such as day or night) returning to its first position before recycling. Example of cyclic processes are shown in table 3, along with examples of responding event, response time, and an indication of the sampling strategy for obtaining data through remote sensing.

Evolutionary or developmental processes, on the other hand, are characterized by a beginning at an initial state, a progression through successive changing states, and an arrival at a climax condition (or goal) in which the environmental makeup is of a different nature than at the beginning. Examples of such processes are ecological succession and economic growth and development, as indicated in table 4. For both these processes, regular monitoring programs need to be set up to identify regions of fastest change as well as other important parameters.

In general, the processes that govern cyclic changes in the environment are better understood than those governing developmental changes. The developmental changes, however, are high on the agendas of all nations as we enter the decade of the 1970's, because of such crucial changes as rapid population growth coupled with increased expectations

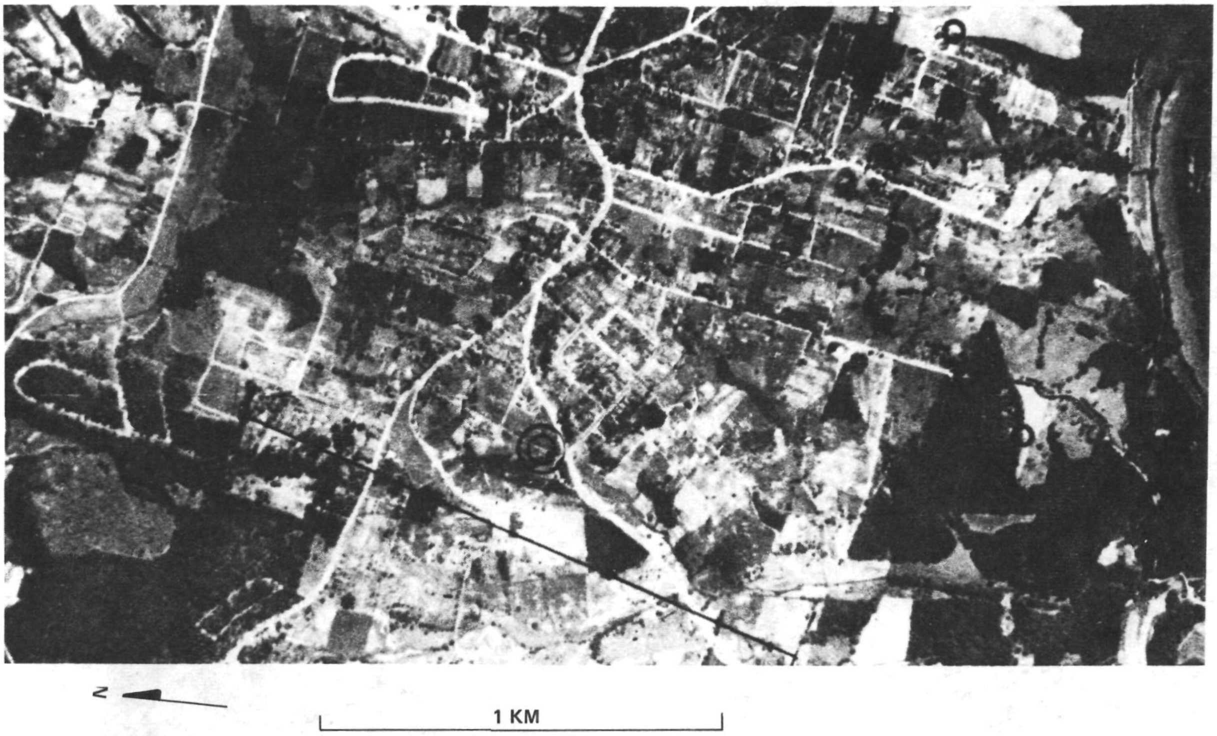

FIGURE 5. Aerial photo of West Asheville, 1924.

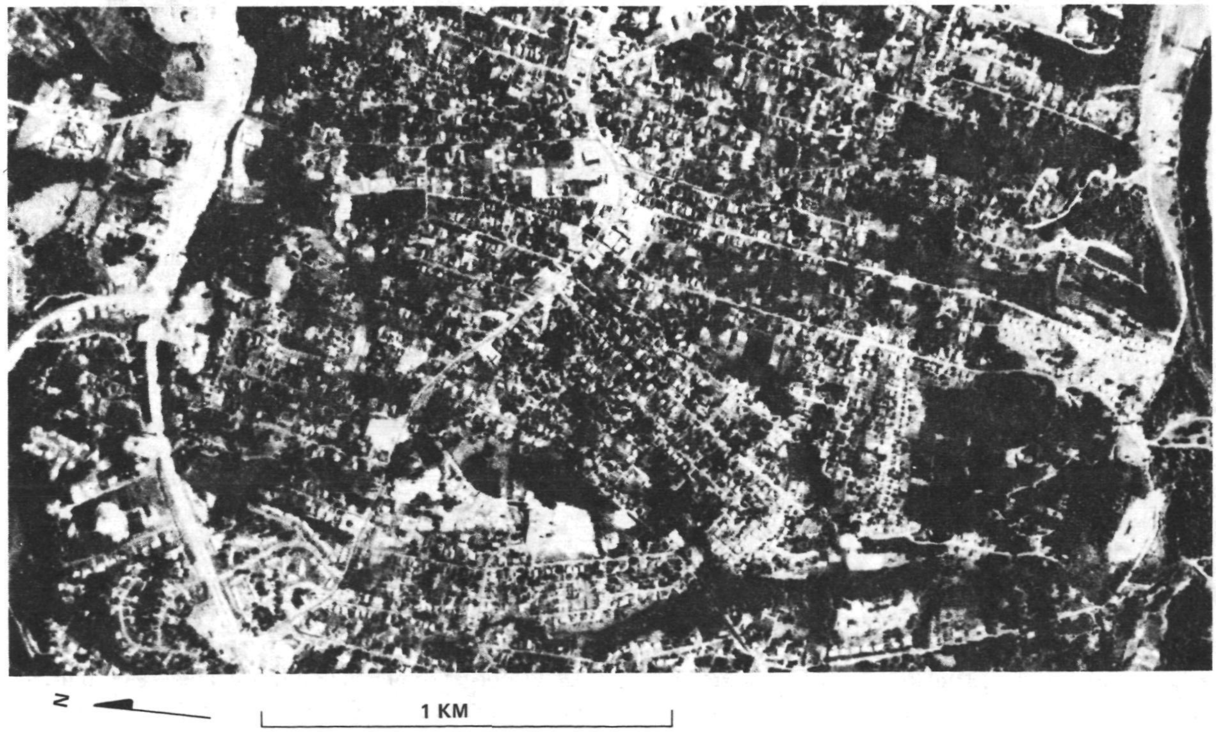

FIGURE 6. Aerial photo of West Asheville, 1963.

FIGURE 7. Color IR photo showing sugar beet field being harvested, Imperial Valley.

in terms of standard of living and preservation of environmental quality. For these reasons there is a great urgency for early applications of Earth resources information systems, based on new data that can be supplied by remote sensors in monitoring the environmental and developmental changes that are now taking place. Furthermore, the developmental processes themselves, such as the impact of changing industrial and urban systems on land use and environmental quality, will be better understood as we accumulate new time-series data sets on the regions where change is fastest.

MONITORING REGIONAL DEVELOPMENT

Sequential remote sensing views of a region can be used as a source of data on regional change, as shown in figures 10 thru 15. To illustrate how data from airborne and spaceborne remote sensors might be incorporated into an operational system for monitoring regional or national environmental change, let us postulate a series of steps to be undertaken, approximately but not strictly in the order presented as follows:

1. Articulate the *goals* and *development models*

FIGURE 8. Ground photo of sugar beets being harvested, Imperial Valley.

Table 2. Categories of processes which produce environmental change

Processes	Scope
Geological processes	Pertaining to the solid Earth, such as rock-forming, deformation, regional tectonics, weathering, soil-forming, glaciation, etc.
Hydrological processes	Pertaining to the action of water, whether underground, in surface water bodies, or in the atmosphere; solution, infiltration, flow in porous media, stream flow, erosion, sedimentation, etc.
Oceanographic processes	Actions of oceans, bays, and estuaries; current motion, wave action, coastal and submarine erosion, etc.
Atmospheric and climatological processes	Planetary wind systems, air-mass dynamics, storm systems, movement of air-borne matter, energy exchange in the Sun-Earth-atmosphere system, etc.
Biological processes	Action of plants and animals, growth, respiration, transpiration, reproduction, energy conversion, resource conversion, including effects of both natural and agricultural vegetation.
Socioeconomic processes	Processes set in motion by man himself and underlain by a complex of historical, cultural, racial, ethnic, and demographic factors; processes include population growth, resource conversion, urbanization, industrialization, trade, education, economic development, transportation, communication, government, conflicts, etc.

FIGURE 9. Coastal changes after hurricane Beulah damaged Texas coast in September 1967. Photo at right was taken 15 months later.

Table 3. Cyclic or periodic processes

Primary processes	Event	Response time	Sampling strategy for remote sensing
Earth rotation (diurnal)	Daily variation of temperature	Minutes to hours	Optimum time of day
	Change in length of shadows	Zero	Optimum time of day
Earth revolution (annual)	Seasonal progression	Days to weeks	Optimum time(s) of year, quick-response capability
Long-term or irregular climatic cycles, geophysical events	Sea-level changes, earthquakes	Years	Systematic monitoring

Table 4. Evolutionary or developmental processes

Primary process	Event	Response time
Ecological succession	Fire, flood, landslide	Days to years
	Change in grass-land-forest mix	
Economic growth & development	Increase in urban areas	Months to years
	Increase in irrigation agriculture	
	Clearing of forests	

underlying the development program. These goals will be based upon *national priorities*, concerning, for example, population, standard of living, employment, industrialization, land use, transportation systems, and environmental quality. Costs and benefits of alternative schemes must also be considered.

2. Develop a basic resource *inventory* to serve as a data base from which change is to be measured. The inventory will include geologic factors, mineral resources, soils and land capability, climate, vegetation, land use by type and area, probable environmental hazards, and human and technological resources. All of the above must be quantified for standardized comparisons as governed by the development models.

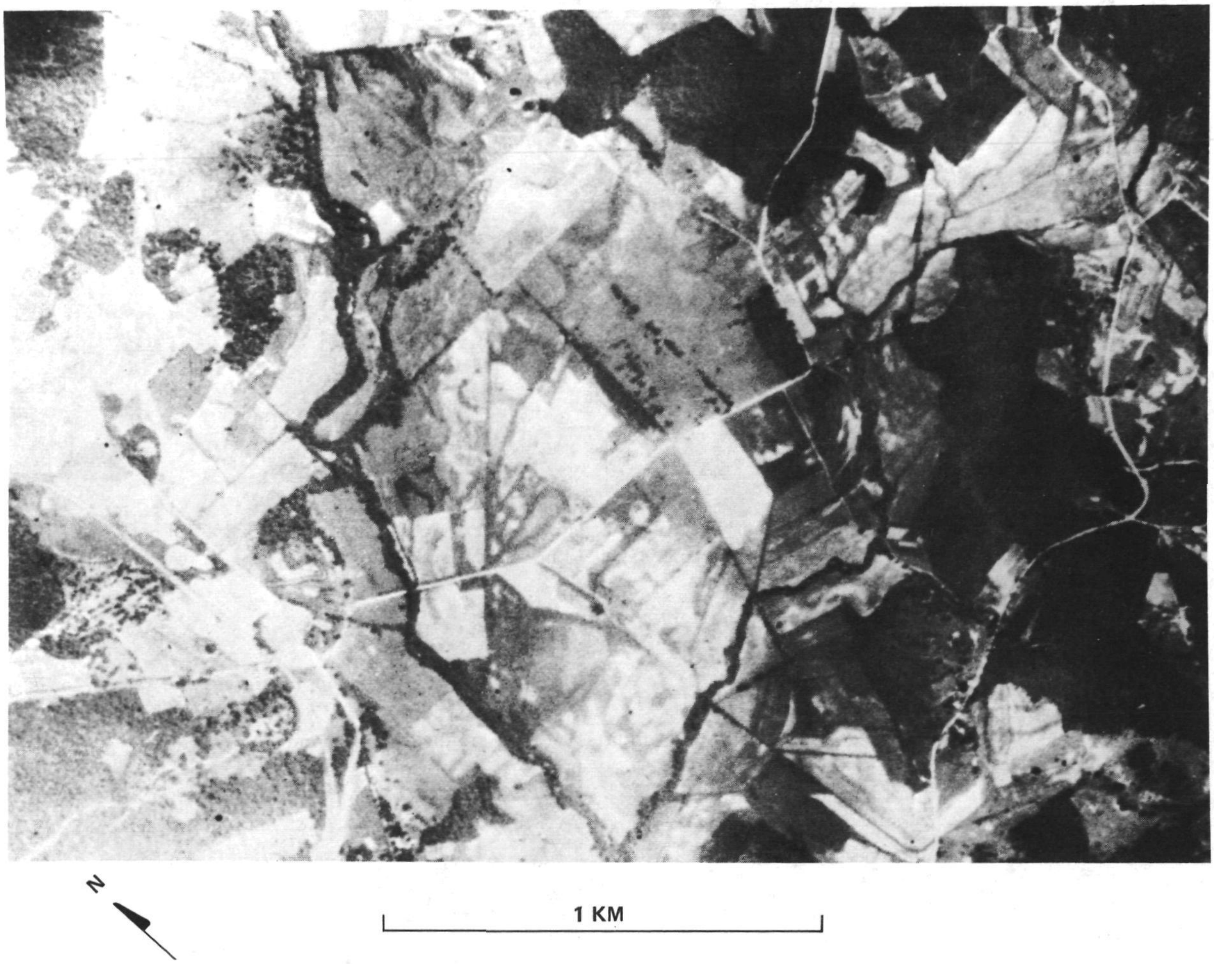

FIGURE 10. Aerial photo of Cane Creek area, Asheville Basin, 1924.

3. Participate in *pilot projects* or experimental demonstrations employing new remote sensing systems for monitoring environmental change. This step is necessary so that the new systems will be tested in a specimen of the special operational environment which may be peculiar to the region, and so that the new techniques may gain acceptance among the user institutions. The demonstration projects will also examine the environmental process models which are most appropriate to the regional circumstances. The environmental process models will aid in specifying types and quantities of remote sensing data to be collected.

4. Develop regional or national *information systems* for assuring adequate delivery of data to the users, in map and other appropriate formats. Regional data centers and computer-assisted information handling techniques may facilitate the development of appropriate information systems.

5. Develop the necessary *skills* and *education programs* to assure that the resource planning and managing institutions will have the manpower re-

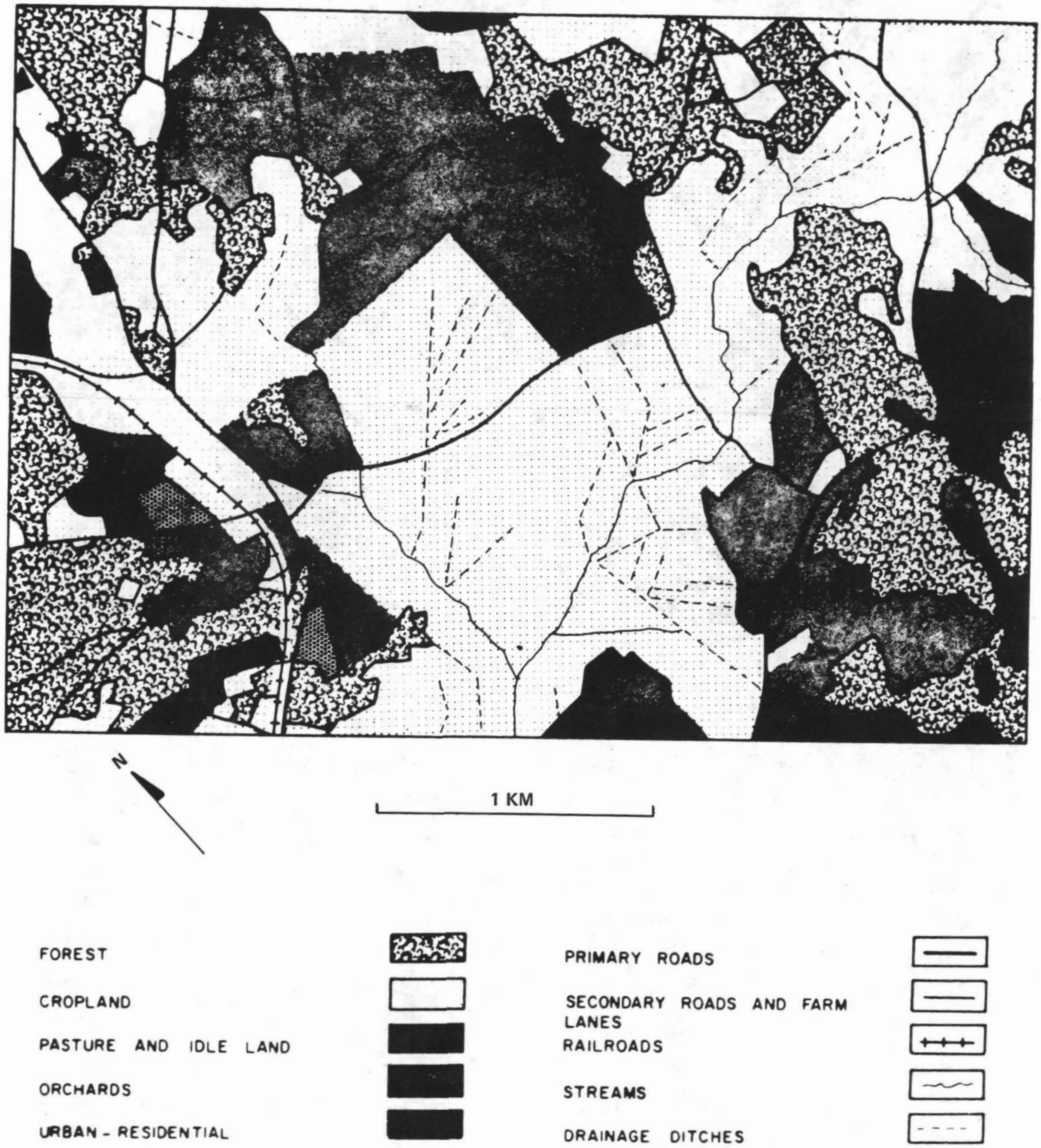

FIGURE 11. Land use map of Cane Creek area, 1924.

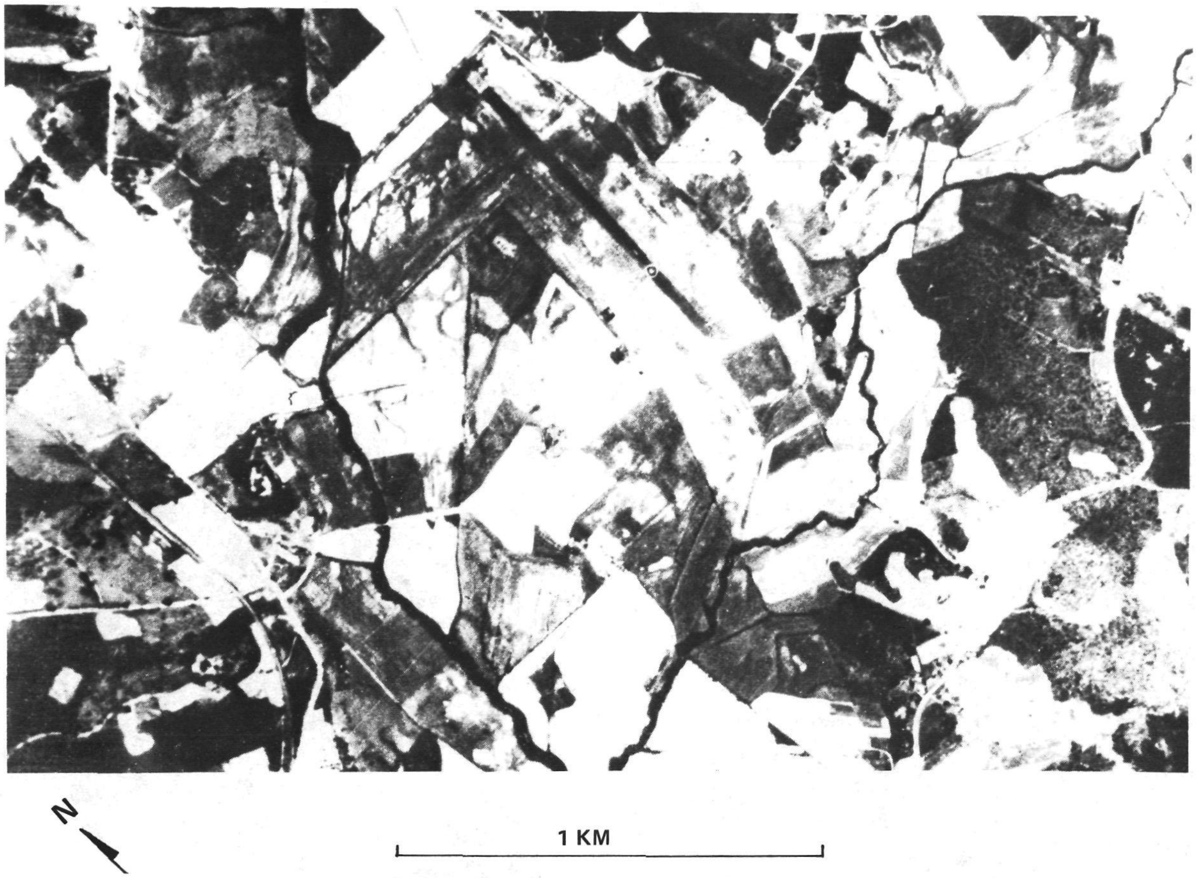

FIGURE 12. Aerial photo of Cane Creek area, 1940.

sources necessary to incorporate the new remote sensing data into action programs.

6. Based on the results of the above steps, establish an *operational program* for regularly obtaining the periodic remote sensing data and other correlative data as required, for operationally monitoring land, water, and air resources throughout the critical period of growth and development. Upon achievement of stability after developmental goals have been attained, it will probably be desirable to maintain the monitoring system to measure environmental quality and receive warning of environmental hazards or disasters.

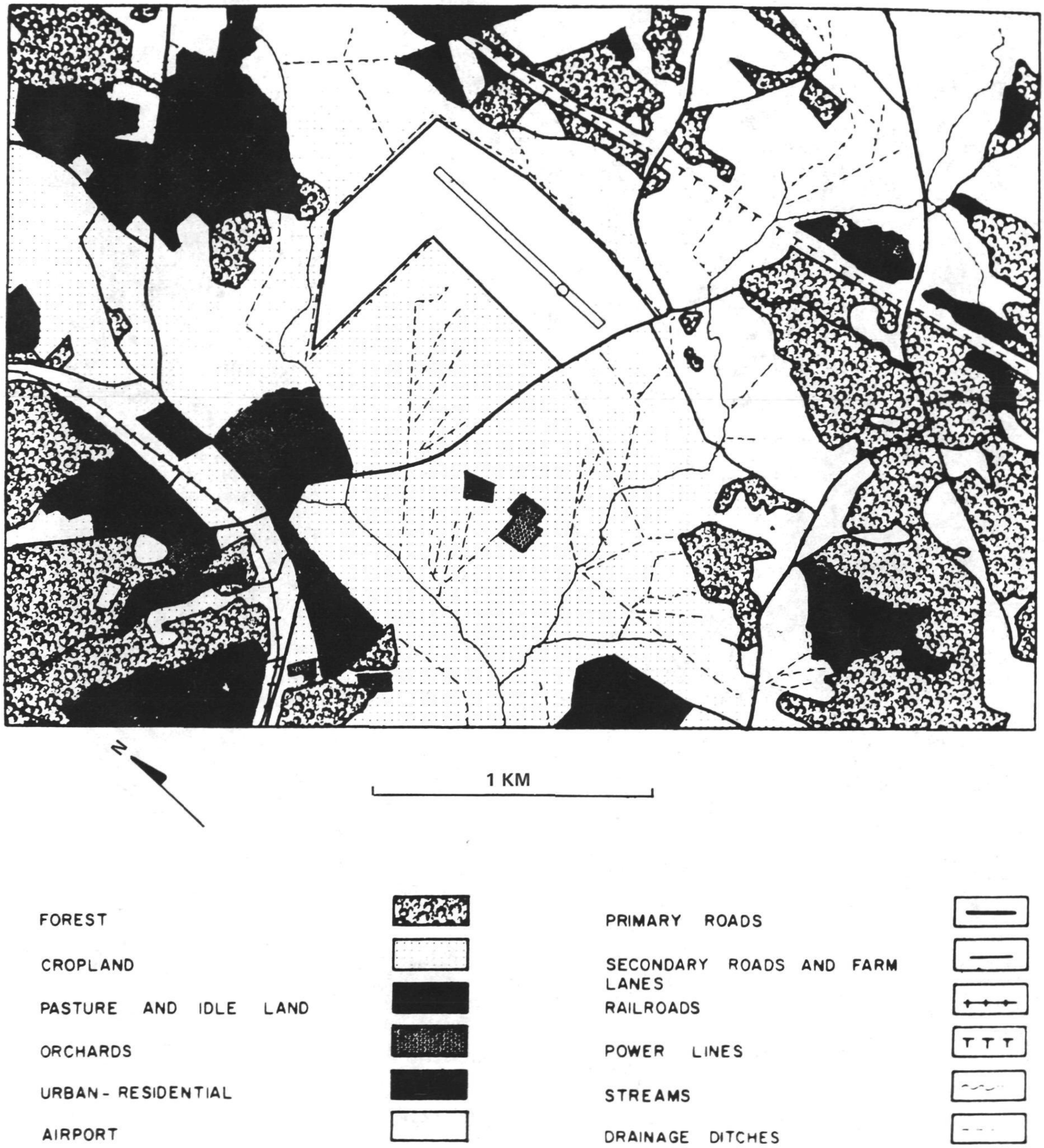

FIGURE 13. Land use map of Cane Creek area, 1940.

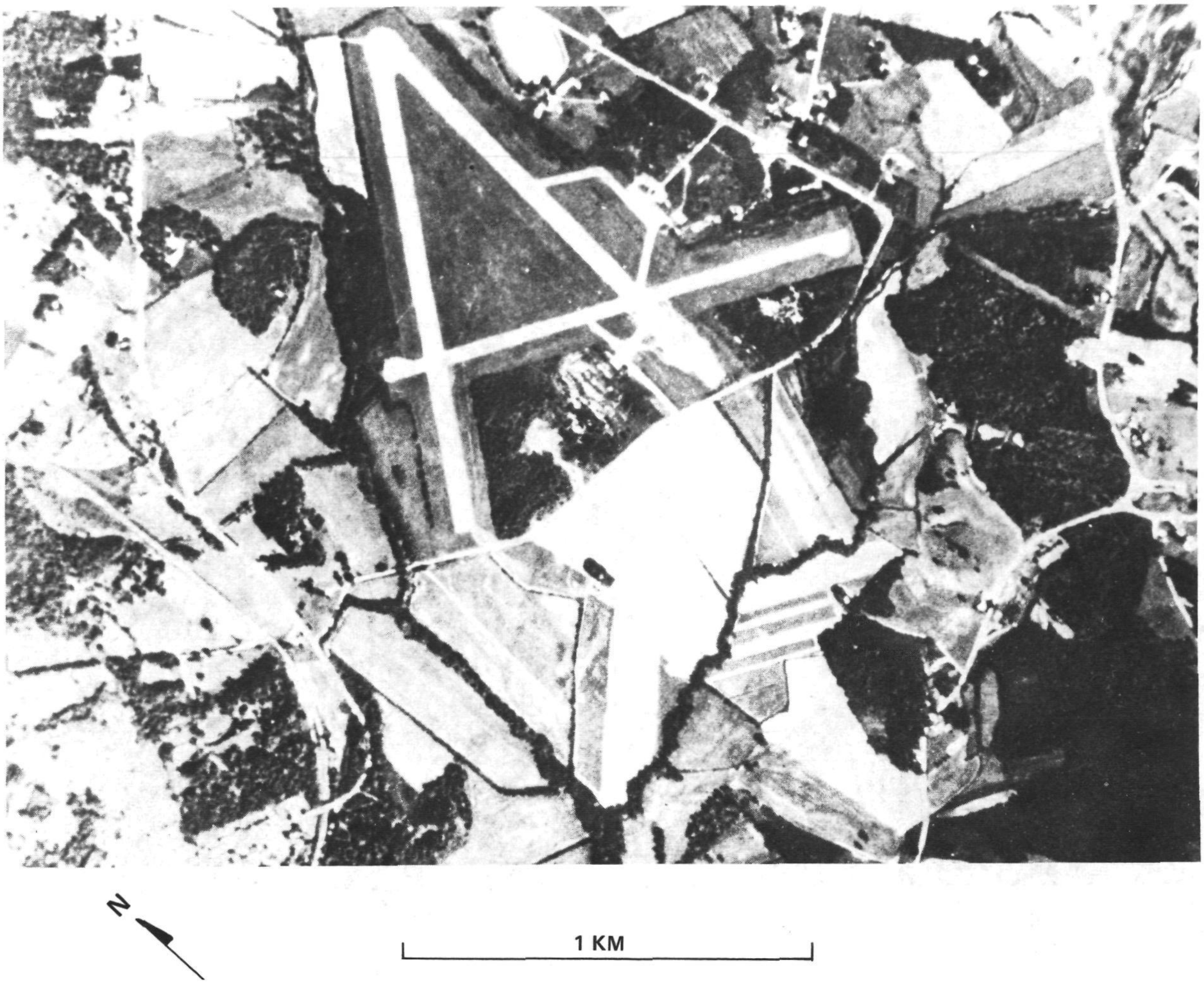

FIGURE 14. Aerial photo of Cane Creek area, 1966.

CONCLUSION

In summary, the new remote sensing technology shows considerable promise as an aid in monitoring time-variant phenomena in the development of regional and national information systems for Earth resources surveys. The new technology will be more effective when combined with appropriate knowledge of cyclic and developmental environmental processes and when incorporated into an appropriate strategy for building operational monitoring systems as required by the goals and priorities of each nation.

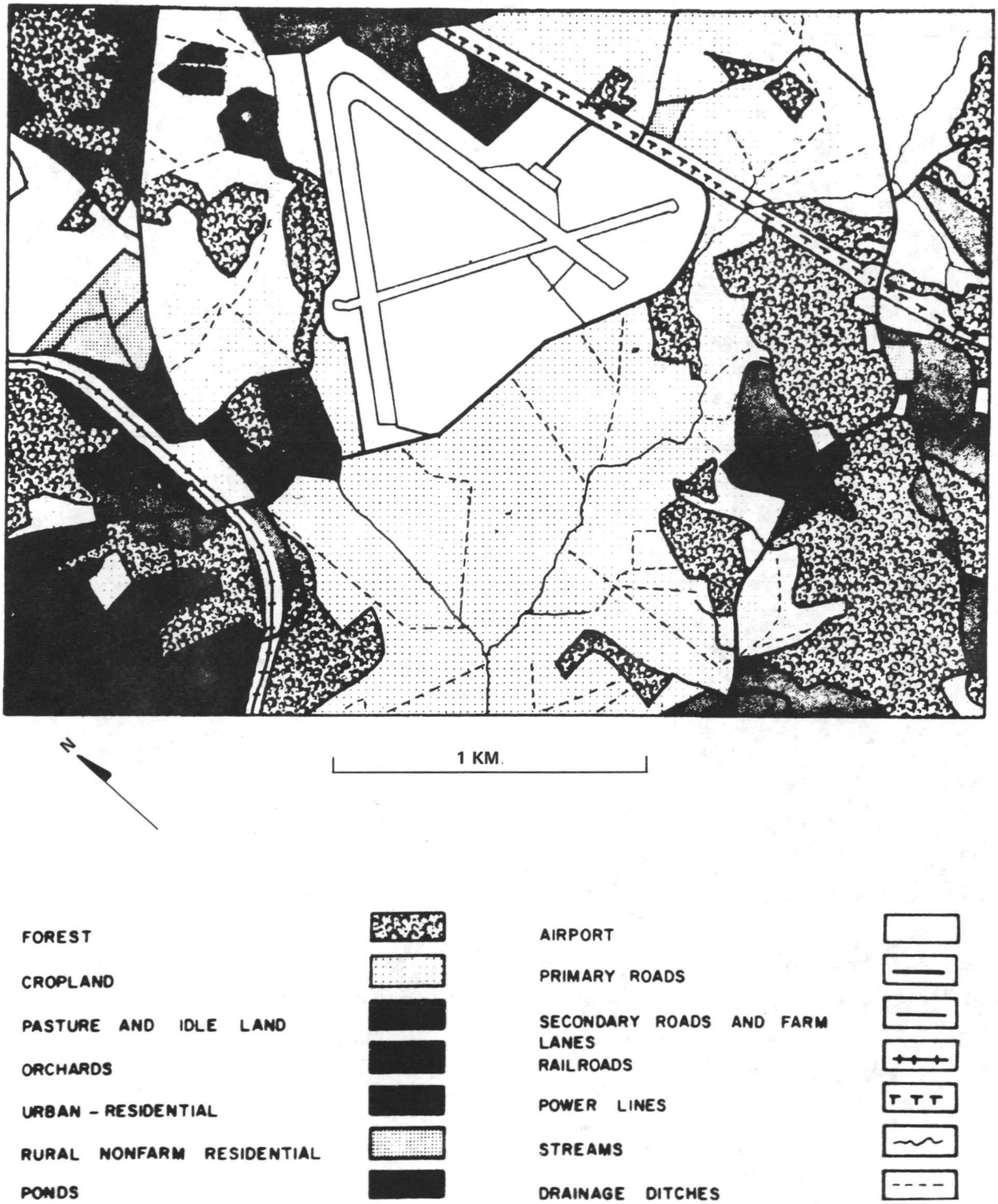

FIGURE 15. Land use map of Cane Creek area, 1966.

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Interpretation of Spatial Relationships

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What one can determine about an object by examination of its image produced by a remote sensor depends upon the size and the quality of the image. Scale is the ratio of the image size to the object size. Image quality is most easily expressed by resolution—which is defined for a continuous-tone optical image. Resolution is highly dependent upon the contrast of an object with its background. For a TV or line-scan system, $2\sqrt{2}$ lines are equivalent to one photographic line pair at high contrast and about 4 scan lines at low contrast.

Although resolution is a useful number for comparing the performance of two imaging systems, it really says very little about the minimum size object which one can detect or interpret from the record. That depends primarily upon how much additional background information the interpreter brings to the task. Since the resolution of the unaided human eye is between 5 and 10 line pairs per millimeter, a remote sensor record can be usefully enlarged until its equivalent resolution is about that number.

No matter how successful the interpreter has been in extracting information from a record, the value of that information may be degraded if one cannot tell where it came from. This implies a reference system, and for the United States the Universal Transverse Mercator metric grid system has been adopted for Earth resource surveys.

Correlation of record detail with an existing reference base is the most common procedure for determining position, and the human eye and brain is the best pattern recognition device. This works well for sensors whose geometry is similar to that of the eye. For other sensors, the complete geometry must be analyzed and corrected either by analog or digital simulation.

The Earth Resources Technology Satellite (ERTS) will carry television and line-scan sensors. The bulk processing element of the ground data handling system will provide approximate position information and record correction. A portion of the data will go through the precise processing element, which will correct all known errors in the record, position it with respect to the Universal Transverse Mercator projection, and print the data at a 1:1 000 000 scale.

It seems perfectly obvious that the amount of information one can extract from a remote sensor record will depend upon the size of the record and its quality. And the value of the information may often depend upon knowing exactly where it came from on the Earth's surface. These three factors—scale, resolution, and spatial position—are determined by analyzing the geometrical characteristics of the sensor record. It is necessary to understand them in order to evaluate the application of the sensor to particular problems.

RECORD SCALE

The ratio of the size of an element of information on a record to the size of the actual object recorded in that element is the record scale, usually expressed as a dimensionless fraction:

$$\text{Scale} = \frac{\text{record dimension}}{\text{object dimension}}.$$

If 1 kilometer on the ground is recorded as 3 mm on the record,

$$\text{scale} = \frac{3\text{ mm}}{1\text{ km}} \times \frac{1\text{ km}}{10^6\text{ mm}} = \frac{1}{333\,333}.$$

The reciprocal of scale is the scale number; that is, for the example given the scale number is 333 333. The two terms are often used interchangeably.

Scale, S, is frequently computed by measuring the dimensions, on the record, of the image of a known object. Any uncertainty in the measured dimension or the known object dimension causes an uncertainty in the computed scale. For example, if

$$\frac{3 \pm 0.1 \text{ mm}}{1000 \pm 1 \text{ m}} = S,$$

$$1{:}345\,173 < S < 1{:}322\,258.$$

A scale number of 330 000 would express all the precision inherent in this computation. The precision with which scale can be determined is obviously a limiting factor in establishing the dimensions of unknown objects by measuring their images on the sensor record. The interpreter must always be aware of how much he doesn't know as well as how much he does know.

There is an obvious advantage if the scale is constant all over the record. In such a case any distance measured on the record multiplied by the scale number will give the corresponding distance on the Earth's surface:

$$(\text{record dimension}) \times (\text{scale number}) = (\text{object dimension})\text{; e.g.,}$$

$$(2.38 \text{ mm}) \times 333\,000 = 790 \text{ m}.$$

However, only in exceptional cases will a sensor produce a constant-scale record.

The simplest imaging sensor is a frame camera (figure 1). In an ideal situation, the camera axis is vertical and the Earth may be considered a plane surface. For that situation,

$$S = \frac{\text{image dimension}}{\text{object dimension}} = \frac{\text{focal length}}{\text{flight altitude}}.$$

In reality, of course, the Earth's surface is not flat. Variations in the topographic relief h mean that the height above ground is variable within the area covered by the photograph. Also, any unit distance on the ground is not necessarily horizontal but may have some slope. Furthermore, despite the best of intentions and the most elaborate stabilization equipment, only rarely will the camera axis turn out to be truly vertical. There is usually some angle of tilt t between the camera axis and the vertical. In such a case the scale will differ from point to point on the photograph. Furthermore, even at a point, the scale will vary, depending on the direction in which it is measured on the photograph. As illustrated in figure 1, for a tilted photograph, scale in the x direction at point i is

$$S_x = \frac{f \cos t - y_i \sin t}{H - h_i};$$

scale in the y direction at point i,

$$S_y = \frac{(f \cos t - y_i \sin t)^2}{f(H - h_i)}.$$

Although variation in record scale is sometimes inconvenient for the interpreter, it is not all bad, because it is actually analysis of scale variation that makes possible the determination of terrain relief for topographic maps.

For sensors which do not record the image optically on a plane surface, the computation of scale becomes increasingly complicated. Panoramic cameras, line scanners, side-looking radar—each has a unique geometry which results in a variable scale at all points in the record. The analysis of these scale variations is a function which the photogrammetrist performs for the remote-sensing community.

SENSOR RESOLUTION

The ability of an imaging system to record fine detail of the object is one measure of image quality. If an object field consisting of alternating light and dark lines at decreasing spatial intervals is recorded by an imaging system, there will be some interval at which it is no longer possible to clearly separate the lines and spaces when the image is viewed under optimum magnification. The number of such line pairs (one dark and one light line) recorded in 1 millimeter is the *image resolution*. It is frequently given in lines per millimeter, but to avoid confusion "line pairs per millimeter" (lp/mm) or "cycles per millimeter" is preferred.

Many things affect the resolution of a sensor system. These include:

- Contrast of the object field
- Lens design
- Field of view
- Wavelength of light
- Transmission of the atmosphere

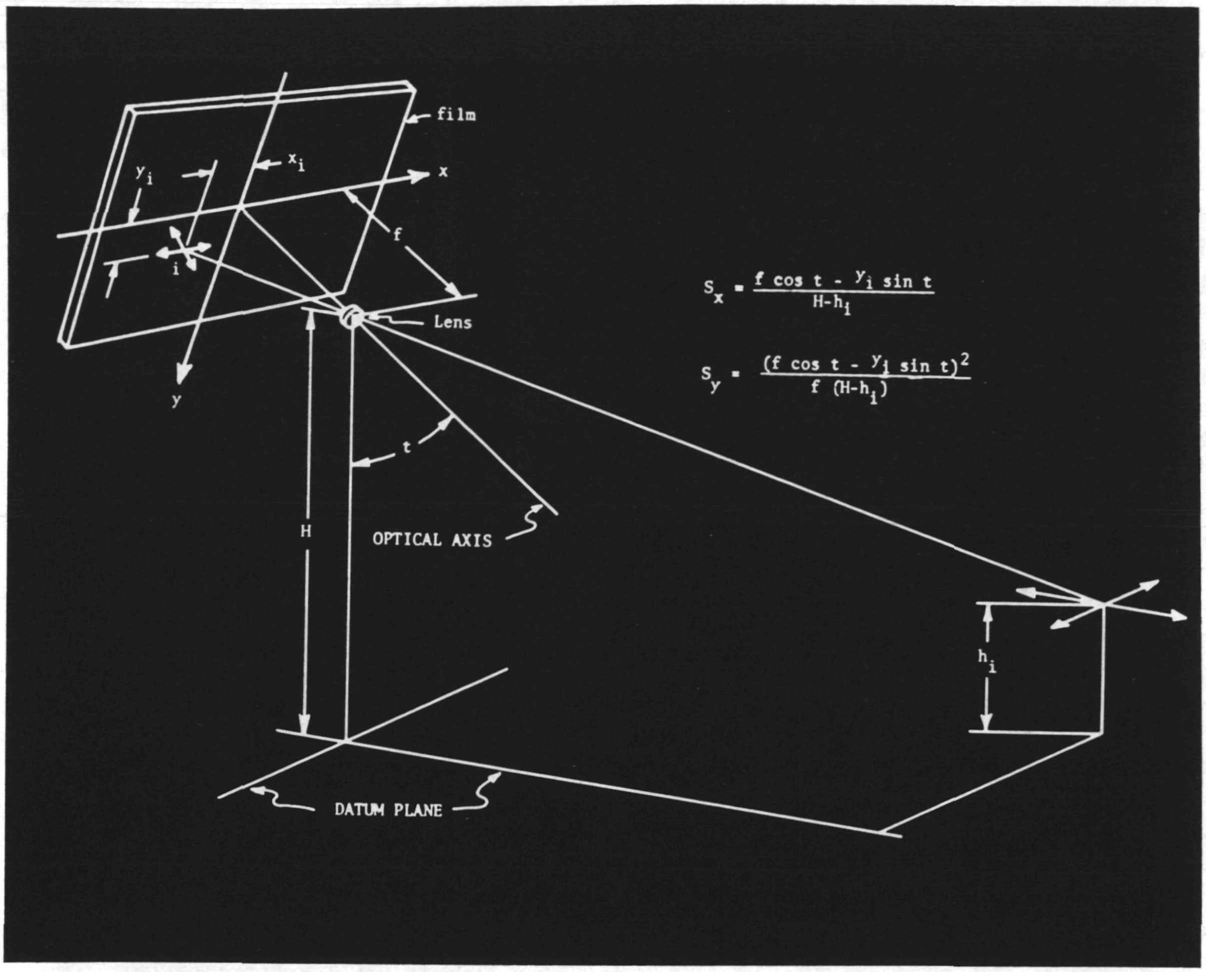


FIGURE 1. Scale factors on tilted aerial photograph.

- Image motion
- Grain size of the emulsion
- Exposure level
- Photographic processing

Each of these must be taken into account in evaluating the resolution of a photographic system.

One of the most critical factors is the contrast of the recorded image. There are a number of mathematical definitions of contrast, but they all relate to the difference in brightness of an object and its background. The effect of most of the conditions listed above is to reduce the contrast from the object field to its image on the film. As the contrast decreases, the resolution of the image falls off rapidly as shown in table 1.

Table 1. Resolving power for aerial films

Film		Resolution (*l*p/mm)	
Name	Number	Contrast 1000:1	Contrast 1.6:1
Plus-X	2402	100	50
Tri-X	2403	80	20
Pan-X	3400	160	63
High definition	3414	630	250
BW infrared	2424	80	32
Color infrared	2443	63	32
Aerial color	SO242	200	100

Unfortunately, optical systems are usually tested with high-contrast targets, whereas the contrast of actual aerial scenes is much closer to 1.6:1. It is essential that the target contrast be specified when resolution numbers are quoted.

The basically simple system of measuring photographic resolution has been complicated and confused by the introduction of television and other types of electrooptical line-scan sensor systems. In addition to having a resolution limit imposed by the detecting surface, further limits are imposed by the electronics and geometry of the scanning process. As shown in figure 2, the direction of the scan spot movement along the lines of the test pattern is called horizontal; across the test pattern the spacing of adjacent scan lines is the vertical direction. The resolution in the vertical direction depends on the diameter of the scanning spot because this determines the width of each scan line. Horizontally, the resolution is restricted by the bandwidth or rise time of the amplifier which permits a change in the amplitude of the signal. In most scanning systems the horizontal and vertical resolutions are made approximately equal. It is important to realize that the scanning spot simply integrates all the energy within its area. As a spot of finite diameter moves across the line from a dark to a light space, the energy will increase gradually, and thus an absolutely sharp edge between light and dark areas can never be recorded.

It is clear from figure 2 and reference 1 that the resolution stated in TV lines is *at least* twice as large *numerically* as the resolving power of film expressed in line pairs per millimeter, because the film resolution was defined in terms of a combined line and space. If the diameter of the scanning beam equals the width of a line alone, and one scan traces along a line while the succeeding scan traces the space, the target will presumably be perfectly resolved. Apparently two TV lines are equivalent to one photographic line pair, and the ratio 2 TV lines per photographic line pair appears frequently in literature. However, if all the scan lines are shifted by half their diameter, nothing will be resolved because each scan will trace precisely half a line and half a space. Thus it really takes more than two TV lines to reproduce one photographic line pair. The convention frequently adopted and strongly recommended for high-contrast targets is

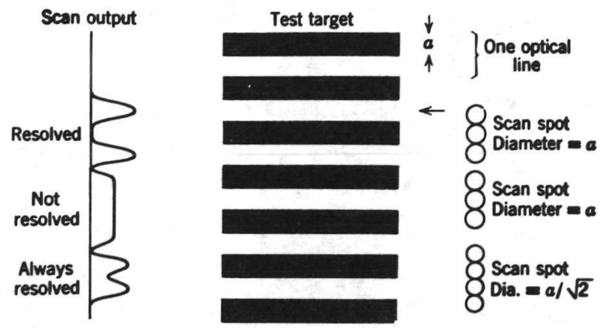


FIGURE 2. Resolution of television system (from ref. 1).

$$(2\sqrt{2}\ \text{TV lines}) = (1\ \text{photographic line pair}).$$

Television engineers frequently express the resolution of an image tube as the total number of scan lines over the tube face. It is therefore necessary to know the faceplate dimensions in order to convert to equivalent photographic resolution. For example, the return beam vidicon (RBV) tubes to be used on the Earth Resources Technology Satellite (ERTS) will have 4100 TV lines on a 25-mm format. There are thus $4100/25 = 164$ TV lines per millimeter. This is equivalent to $164/2\sqrt{2} = 58$ photographic lp/mm. In other words, a 58-lp/mm film system will give about the same performance as a 164-TV-lines-per-millimeter television system.

For all types of imaging systems—film, TV, line-scan—the dimension of an image resolution element multiplied by the image scale number is the *ground resolution*. This is frequently, though mistakenly, interpreted as the smallest object which an interpreter can "see" on the record. It is a useful measure to compare the relative performance of several imaging systems, but not to assign limits to objects which can be seen.

The ground resolution of the RBV imagery from ERTS may be computed as follows. Image scale number $1/S$ is:

$$\frac{1}{S} = \frac{H}{f} = \frac{915\ \text{km}}{125\ \text{mm}} \times \frac{10^6\ \text{mm}}{\text{km}} = 7.3 \times 10^6.$$

Ground resolution (TV criterion) is:

$$\frac{\text{mm}}{164\ \text{TV lines}} \times 7.3 \times 10^6 = \frac{45\ \text{meters}}{\text{TV line}}.$$

Ground resolution (photographic criterion) is:

$$\frac{\text{mm}}{58\ \text{line pairs}} \times 7.3 \times 10^6 = \frac{126\ \text{meters}}{\text{line pair}}.$$

Figures like these make the film people unhappy because, to the uninitiated, the film camera system apparently is poorer than the television system. To make the film system look better, the photographic engineers unfortunately adopted another term, *ground resolved dimension*, which is simply the width of one of the target bars—either black or white. Quite obviously, this is simply half the ground resolution. So exactly the same image quality can be described in three ways:

TV resolution	45 meters/TV line
Photographic resolution	126 meters/line pair
Ground resolved dimension	63 meters/line

It is essential to understand exactly which criterion and definition is being applied when one hears "the system resolution is 50 meters."

It often happens that the resolution of a sensor image is variable over the format. Photographic lenses and television tubes, for example, have lower resolution in the corners than in the center. Other sensors, like the multispectral scanner in the ERTS satellite, have nearly constant image resolution. However, as has been mentioned, there may be considerable variations in the scale of the record due to its geometry. Consequently the ground resolution may vary considerably from point to point. Both factors must be taken into account in evaluating the performance of a sensor system.

Line-scan systems, like film systems, have lower resolution when the target contrast is reduced. Here again, an unfortunate and confusing convention has been introduced. Television engineers may speak of *equivalent line resolution*. The ERTS sensor, as has been pointed out, has 4100 scan lines and at 1000:1 contrast it takes $2\sqrt{2} = 2.8$ scan lines to resolve a photographic line pair. At 1.6:1 contrast it takes about 4.0 scan lines to resolve a photographic line pair. Then the equivalent TV resolution is:

$$\frac{45\text{ m}}{\text{TV line}} \times \frac{4}{2.8} = \frac{64\text{ m}}{\text{TV line}}.$$

The number of TV lines per millimeter is:

$$\frac{64\text{ m}}{\text{TV line}} \times \frac{1}{7\,300\,000} = \frac{\text{mm}}{114\text{ TV lines}}.$$

Equivalent line resolution is:

$$\frac{114\text{ TV lines}}{\text{mm}} \times (25\text{ mm}) = 2850\text{ lines}.$$

Thus, though there are actually still 4100 scan lines on the tube, the television engineer may say "the equivalent line resolution for low-contrast objects is 2850 lines," or, though each TV line actually represents 45 m on the ground, he may say, "the equivalent resolution for low-contrast targets is 64 m/TV line."

There are other measures of image quality besides resolution. Principal among these is *modulation transfer function*. It is more informative than resolution, but it is much more difficult to determine and requires a diagram or a mathematical equation rather than a simple number.

Remote-sensing practitioners have also used the word resolution in two other contexts:

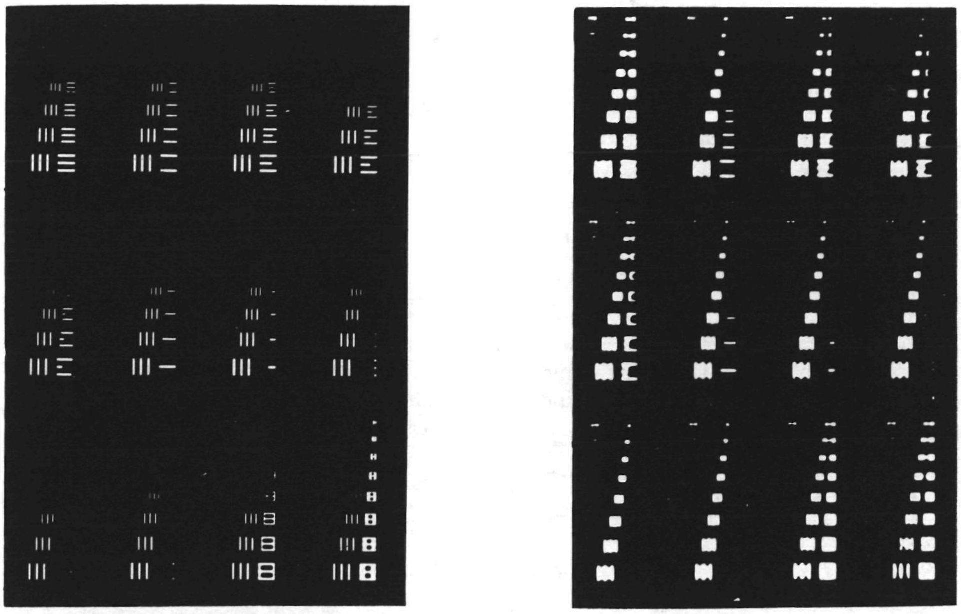
- Spectral resolution—the ability of a system to operate within defined wavelengths of radiation
- Temporal resolution—the ability of a system to operate at selected intervals of time.

INFORMATION CONTENT

If the world were made up of alternating black and white bands, resolution—by any of the accepted criteria—would be a useful method of describing what one could see on the records. The real world, however, is made up of land and water, mountains and plains, forests and fields, urban and agricultural areas, manmade and natural objects. Typically the scene is low contrast and the alternations from light to dark are gradual rather than abrupt.

The ability of an interpreter to distinguish a signal from its background in the image is *detectability*. It is highly dependent on the contrast and continuity of the signal. A point source of light having no dimension at all (such as a star) may easily be detected against a uniform background (sky), whereas a highly reflective rock of finite size might not be detected against a mottled background of terrain. On the other hand a long linear feature, such as a highway, may have the same reflectance and contrast as the rock and be easily detected. In such cases the width of the linear feature may be only 1/10 or less of the ground resolution.

That signals far smaller than a resolution element can be detected is illustrated by figure 3. A series of standard resolution targets were altered by removing or adding parts of the white bars as shown on the left. The altered targets were then photographed at different distances until only the larger



a. Altered resolution targets

b. Degraded copy of targets

FIGURE 3. Detection of signals less than resolution.

targets were resolved. The results are shown on the right. Signals whose dimensions are only one fourth of the resolution element are clearly detected. The figure also illustrates another fact: Light signals against a dark background are detected much more readily than dark signals against a light background. It takes little imagination to realize that no amount of resolution would detect a black cat on a black fur rug.

The ability to assign meaning to a detected signal is called *identification* or *recognizability*. Many investigators have attempted to determine the number of resolution elements needed to identify objects. Three to five resolution elements will permit one to say whether an object is a square, circle, or triangle (ref. 2). But how many resolution elements are needed to tell what the square, circle, or triangle actually represent?

In one test (ref. 3), models of vehicles were photographed from both an oblique and a vertical viewpoint. The pictures were transformed into line-scan images with various numbers of scans per vehicle. Interpreters were asked to identify the vehicles, with the results shown in figure 4; 15 scans per vehicle gave about 80 percent correct identification, with only small improvement for additional scans.

But suppose the interpreter didn't know what any vehicle looked like. Quite clearly an infinite number of scans wouldn't permit him to identify it. Or suppose, instead of vehicles, the objects of interest were field patterns. Three or four scans per field would probably be adequate to delineate the pattern.

Other tests have been performed to determine the effect of the number of gray levels and the signal-to-noise ratio in the images. Not surprisingly, the results turn out to be highly dependent on the class of objects being examined.

What one can conclude is that resolution, like peace, is a good thing to have, but it is no guarantee that one will see what he is looking for. Every different class of objects will require a different resolution, a different number of gray levels, and a different signal-to-noise ratio. And none of these factors are as important as the amount of prior information which the interpreter brings to his task.

SPATIAL POSITIONING

No matter how sophisticated the interpretation of sensor data, its value may be degraded unless the position from which the information came can be determined. Although positional information can be

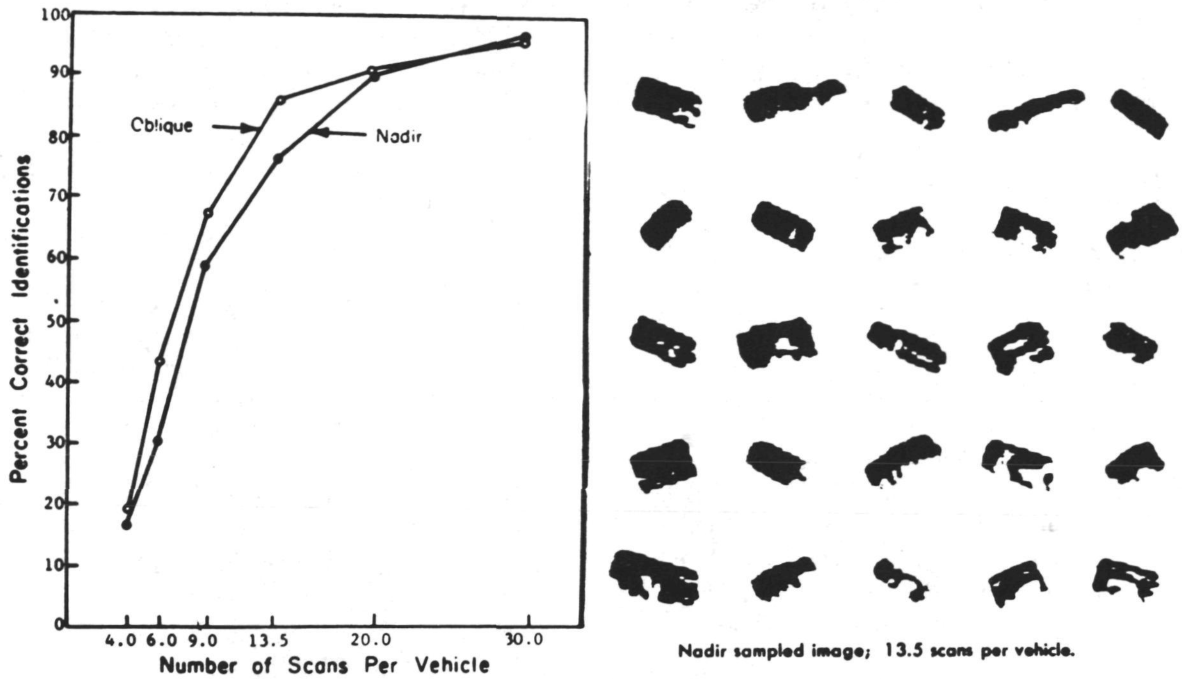


FIGURE 4. Scan lines required for identification.

provided digitally, for most purposes a graphic output is desirable. Cartographic presentation of remote sensor data makes possible

- planimetric and elevation location of resource data
- area measurement of resource data
- relation of resource data to natural and cultural surroundings
- convenient storage of data for comparison of time-variant phenomena.

Spatial positioning implies the existence of a reference system in which positions can be defined. In the United States the Universal Transverse Mercator system with a metric grid has been adopted for referencing remote sensor data. The country is divided into 10 zones, each of which extends 6° in longitude. Within these zones a set of XYZ rectangular cartesian coordinates uniquely identifies any point. This same reference system has been adopted by over 60 nations around the world.

The accuracy of positioning, the ground resolution of the sensor data, and the scale of the map on which the sensor data are presented are interrelated. Under normal conditions the unaided eye can resolve 5 to 10 lp/mm. This means that sensor data can be enlarged until its equivalent resolution is 10 lp/mm. It also means that the appropriate map-scale number for presentation of the data is 10^4 times the ground resolution in meters. U.S. Map Accuracy Standards require that the standard error of map positions should not exceed 0.3 mm at published map scales and that the standard error of elevation should not exceed 0.3 times the contour interval. When these factors are taken into account, they result in the values shown in table 2.

The contour interval is not fixed for a given map scale; an interval adequate to show the character of the terrain will be selected. However, small contour intervals usually go with large-scale maps.

IMAGE DATA CORRELATION

The most common means of positioning remote-sensor data is simply to correlate the image to an existing reference base. This is easily done when the sensor record has essentially the same geometry as the reference—a vertical frame-type photograph to a line-drawn map at the same scale, for example. It is less easily done when the sensor geometry is different from the reference. In such a case, positioning may be done in two steps: for example, an infrared scanner record may be correlated to a con-

Table 2. Map accuracy requirements

Map scale number	Ground resolution	Std. error (position)	Contour interval	Std. error (elevation)
1 000 000	100 m	300 m	100 m	30 m
250 000	25	75	50	15
100 000	10	30	25	8
50 000	5	15	10	3
25 000	2.5	7.5	5	1.5

ventional aerial photograph and then the photograph correlated to a map.

The human eye and brain is an exceptional pattern-recognition device. It readily accommodates changes in basic geometry, differential variations in scale, differences or even reversals in gray level, and additions and deletions of detail. This ability accounts for the large number of human interpreters in the remote sensing business.

Many attempts have been made to perform image correlation automatically. The most common approach is to employ CRT scanning of the sensor record, the reference record, and the output record, as shown in figure 5. The correlation circuitry compares the phase of the signals from the reference and sensor records. By analysis of these differences, the machine determines the necessary scan raster deformations, the differential *xy* translations, and the rotations necessary to match the sensor record geometry to that of the reference. The output tube prints the gray levels from the sensor record in the format and geometry of the reference record. Such devices work quite well when the geometric discrepancies are not gross and when the gray levels are reasonably consistent. Signal amplitude differences—light gray to darker gray—can be accommodated, but arbitrary amplitude reversals—white to black—confuse the correlator. Unfortunately, such reversals are common in comparing the outputs of sensors operating in different bandwidths.

Digital correlation of image data has been accomplished. The signal amplitude versus position on the record is converted to digital information. The computer searches for similar patterns in these

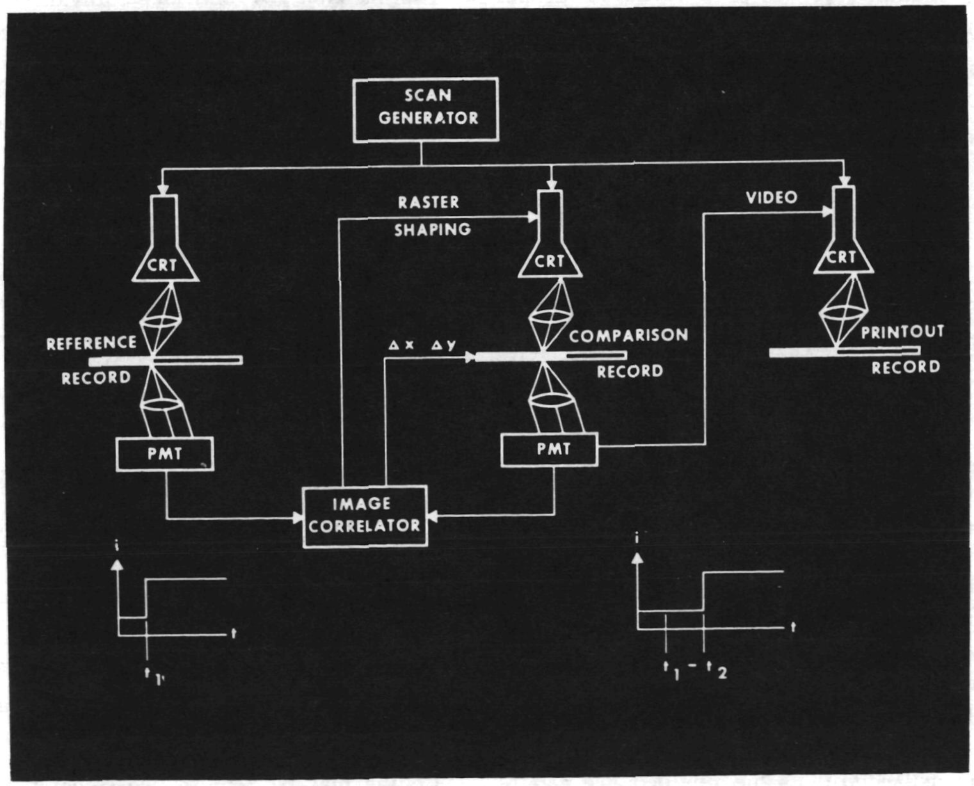


FIGURE 5. Automatic image correlation.

arrays of numbers. Geometric differences are difficult to accommodate, and high-resolution records can require enormous amounts of computer time.

Experiments have also been conducted with either analog or digital correlation of the optical Fourier transform of remote-sensor records. The system works well for optical character recognition, but has achieved only marginal success with the geometric distortions and amplitude differences inherent in most useful remote-sensor records.

With the present state of the art, the most sophisticated machine cannot compare with the ability of the lowliest human interpreter.

GENERAL TRANSFORMATION PROBLEM

The general problem of transforming remote sensor data to a reference system requires a complete geometric analysis of the record characteristics, the sensor geometry, and the position and attitude of the sensor when the data were recorded. The reference-system coordinates are a function of these variables—

$$(XYZ)_{\text{reference}} = f\left\{\begin{array}{l} xy \text{ on record} \\ \text{record errors} \\ \text{sensor geometry} \\ \text{sensor position} \\ \text{sensor attitude} \end{array}\right\}$$

Once this analysis is completed, a system may be devised to perform the transformation. The problem may be handled by either an analog, a digital, or a combined approach. In general an analog system, once built, is more efficient, while a digital system is much more flexible.

Aerial photography with frame-type cameras is the most universal of remote sensors. It is the only one for which a complete analog processing system has been developed. Photogrammetric plotting instruments simulate the interior geometry of the camera, as well as its position and attitude in space, and provide a transformation from the image position on the photograph to the object position in an appropriate reference system. Data from other sensors, such as line scanners and side-looking radar, are usually handled digitally or in combined analog-digital systems.

ERTS DATA PROCESSING

The Earth Resources Technology Satellite (ERTS) will carry two kinds of imaging sensors: three RBV cameras and a multispectral scanner (MSS). Data collected by these sensors will be transmitted to receiving stations where they will be recorded on video tape. The tapes, together with spacecraft data including position and attitude, will go to the image processing subsystem in the NASA data processing facility.

As shown in figure 6, the bulk processing section will convert the video tape into photographic latent

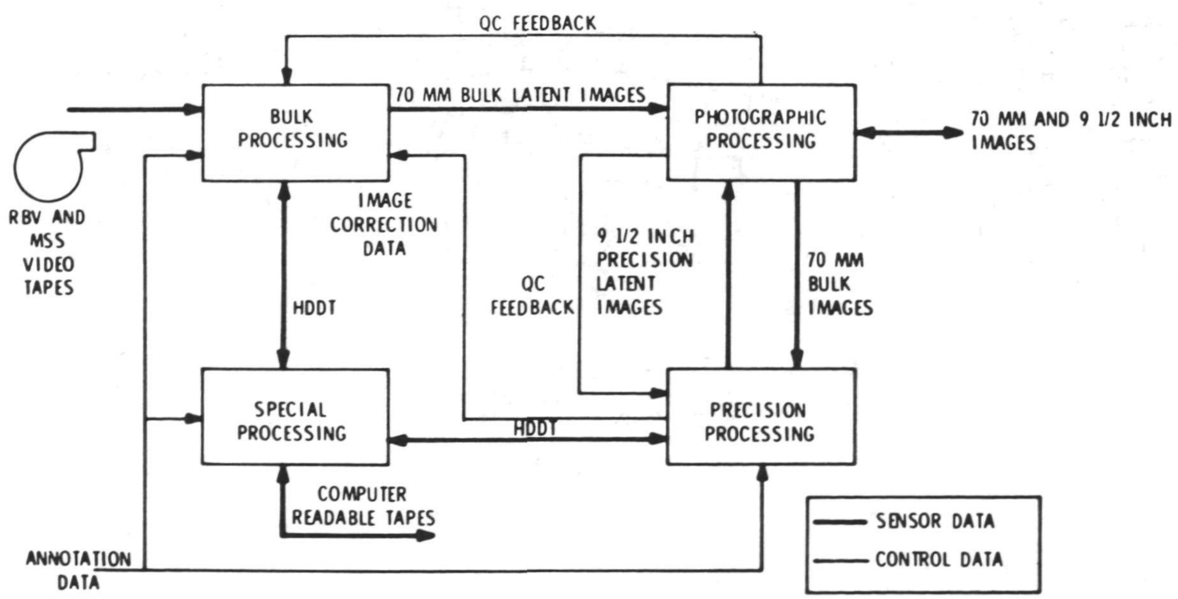


FIGURE 6. ERTS image processing facility.

images on film by means of an electron-beam recorder. The photographic processing section will develop and print the pictures. Some part of the pictures will go to the precision processing section, where the image data will be positioned with respect to the accepted Universal Transverse Mercator grid system. This will require that the images be corrected for the sensor geometry, position, and attitude, as well as for the errors introduced during scanning and transmission. Those errors which are constant for all frames will be passed to the bulk processing section and corrected there.

The RBV is essentially a vertical frame-type camera except that the sensitive surface is the faceplate of a vidicon tube rather than a photographic film. The faceplate of the tube will carry a pattern of engraved crosses (reseau) whose actual positions will be measured before the camera is installed in the spacecraft.

Geometric analysis of the RBV shows that the pictures will be subject to two kinds of errors, as shown in figure 7:

1. First-order errors
   - Offset—due to camera tilt
   - Scale—due to altitude variations
   - Skew—due to camera tilt
   - Rotation—due to spacecraft yaw
2. Second-order errors
   - Lens distortion
   - Scan sweep nonlinearity
   - Raster pincushion distortion
   - Raster S-curve distortion

The result of these errors will be that a square grid on the Earth's surface will appear as a series of curved lines on the image. The first-order errors can be corrected by measuring the positions of image points for which the actual ground reference coordinates are known, or, with less accuracy, by using the spacecraft position and attitude data. The second-order errors can be corrected by measurement of reseau marks on bulk-processed images.

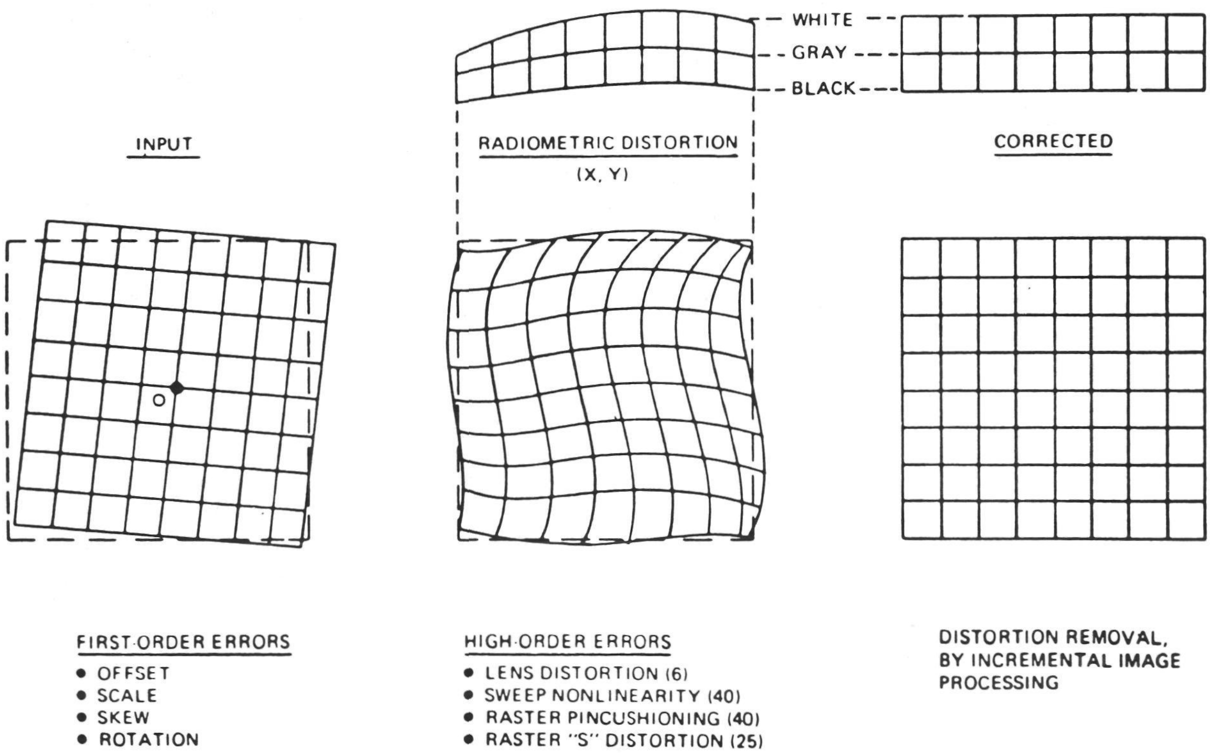


FIGURE 7. RBV image distortions.

The MSS images will also be subject to distortion, as shown in figure 8. As with all line-scanner images, the scale will be variable across the format. Spacecraft attitude variations and Earth rotation will cause a square grid to be imaged as curved lines. These errors can be corrected approximately by knowledge of the sensor geometry and the spacecraft position and attitude, or more precisely by measuring the coordinates of ground reference points.

THE PRECISION PROCESSING SECTION

The precision processing section will perform the following functions:

- Automatic reseau error measurement
- Automatic ground control point measurement
- Computation of image transformation
- Printing and digitizing of corrected images

In order to measure the reseau points, a signal representative of a reseau configuration will be generated. The image will then be scanned, and an image correlator will compare the scan signals with the reseau signals. When correlation is attained, the computer will compare the measured locations with the calibrated locations and determine the reseau position errors.

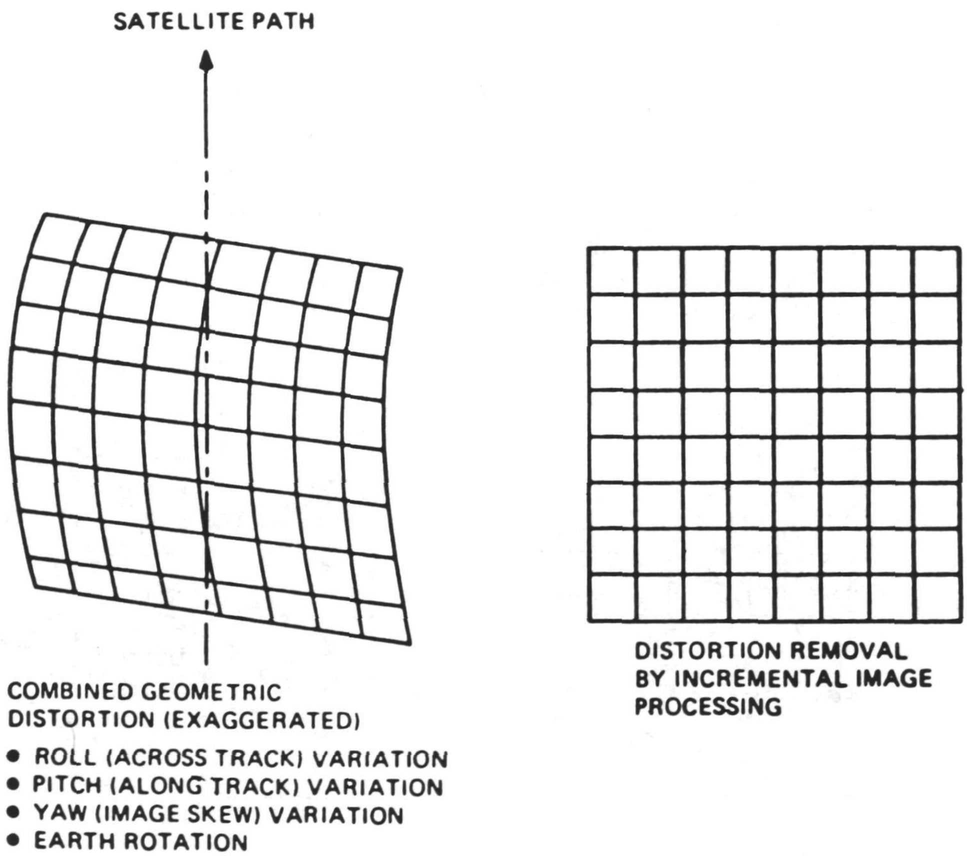


FIGURE 8. MSS image distortions.

Automatic ground-control point measurement will employ a library of known ground point images. The known image and the input ERTS image will be scanned. When correlation between the two images is obtained, the coordinates of the ground control point on the input image will be recorded in the computer. Using the measured information and the mathematical model of the sensor geometry, the computer will then determine the transformations necessary to position the sensor imagery in the selected reference system. These will essentially be polynomials expressing the reference-system coordinates as functions of the measured image-system coordinates.

Finally the corrected image will be printed, as shown in figure 9. The computer will provide raster-shaping signals to the input image-scanning tube and output image coordinates to the table carrying the output film. The video signal from the input image will be radiometrically corrected and then directed to the printing tube.

The resulting output image will be correctly scaled at 1:1 000 000 and printed in a format containing appropriate marginal information, along with geographic and Universal Transverse Mercator grid coordinates. The expected positional accuracy of the data will be as shown in table 3. Reference to table 2 shows that, while the resolution of the ERTS imagery is roughly compatible with the 1:1 000 000 map scale, the positional accuracy obtainable from the precision processing section is better than required. The principal reason for this is the desire to assure registration of the three RBV images.

Table 3. Positional accuracy of ERTS imagery

Parameter	Bulk processing		Precision processing	
	3σ	1σ	3σ	1σ
MSS position	3050 m	965 m	210 m	75 m
RBV position	3380	1025	178	65
RBV registration	870	285	178	65

SUMMARY

The use of remote-sensor records for evaluation of Earth resource data requires research into the essential elements of information which identify various classes of objects. Two critical factors

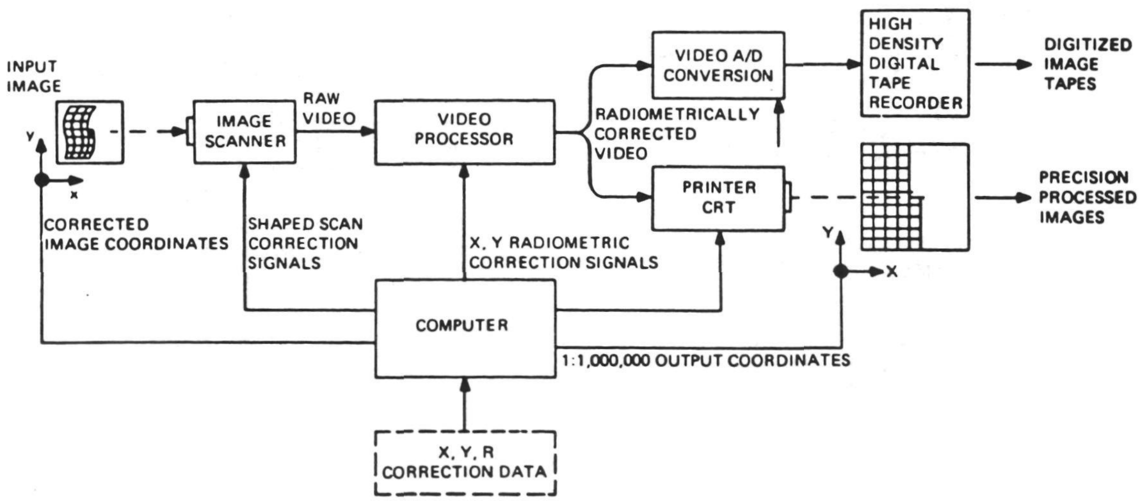


FIGURE 9. Image transformation and printing.

affecting the extraction of information are the scale and the resolution of the record. Both scale and resolution are usually variable over the record format. The product of scale and resolution is ground resolution, which is consequently also variable within the scene. Ground resolution is a useful measure for comparing two sensor systems, but it is not sufficient to tell exactly what one can interpret from the record.

The usefulness of remote-sensing information is frequently dependent upon the ability to tell exactly where on the Earth's surface the information came from. The ability to position data requires a geometric analysis of the sensor configuration and knowledge of its position and attitude when the data were recorded. For the ERTS satellite this capability will be provided by the precision processing section of the ground data handling facility.

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Interpretation by Interdisciplinary Teams

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In the face of dwindling resources and increasing population pressures on our environment, scientists and resource managers of all disciplines must work together to find equitable solutions to the problems of man and his environment. Experiments within the NASA Earth Observations Program are being developed under an interdisciplinary team approach in which scientists from Federal, State, local, and university organizations are studying common remote sensor data to evaluate its application to regional environmental inventory and management problems. This report describes such activities within the State of Arizona.

As we orbit through the vastness of our galaxy, we find that our wonderful spaceship Earth is increasingly beset by problems. Most of these problems are created by man's desire to proliferate and enjoy the material wealth extracted, designed, and produced by his own inventiveness.

The resultant combination of population growth and increased per capita consumption produces increasingly critical shortages of food and nonrenewable resources. In addition, it creates continual pressures on the environment as cities grow and green spaces become smaller.

These shortages and environmental pressures lead to tensions that range from personal to international among men and from local to worldwide among the nonhuman creatures and plants that share our spaceship with us.

The interplay within this complex and sensitive environmental system extends far beyond any single scientific discipline. It is therefore mandatory that interdisciplinary teams be developed if we are to find solutions to many of the complex resource and environmental problems we face today.

Within the NASA Earth Observations Program, we have revised our past disciplinary approach and begun to form interdisciplinary teams which we believe will lead us to perceptive and equitable environmental solutions. The organization of one such team can be visualized as follows:

COMPOSITION OF AN IDEAL INTERDISCIPLINARY TEAM

PROJECT COORDINATOR

ASSISTANT COORDINATOR

Agronomist	Geographer	Cartographer
Biologist	Geologist	Photogrammetrist
Forester	Hydrologist	Meteorologist
Soil scientist	Zoologist	Sensor specialist

The members of these teams represent Federal, State, county, and city organizations as well as universities. At one test site, the specialists include highway engineers, property valuators, and tax assessors. All are attempting to apply common multispectral data collected from aircraft, and soon from satellite platforms, to their particular area of expertise.

Several sites have been selected within the United States where such types of research are being undertaken. Three (in California, Arizona, and the Central Atlantic region) are underway and nine are in the formative stage.

I would like to describe the Arizona Regional Ecological Test Site (ARETS) because it is the one with which I am most familiar. It is also the site that has been most developed. As shown in figure 1, it covers about 86 000 square kilometers.

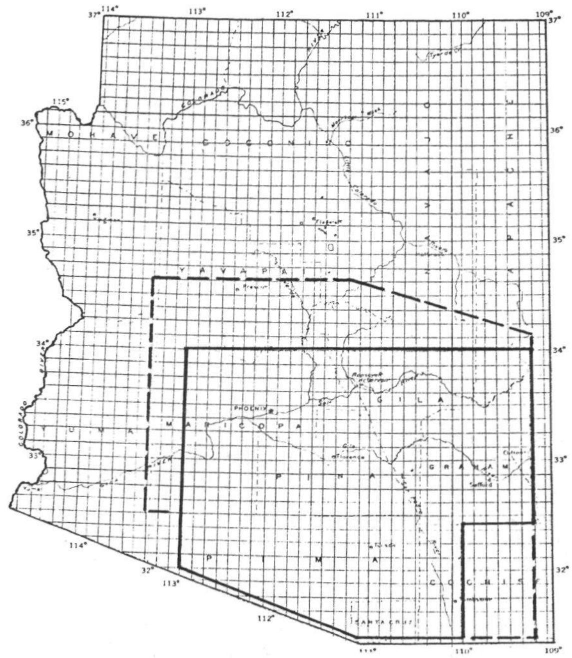


FIGURE 1. Arizona Regional Ecological Test Site (ARETS). Solid line represents area of prime interest (57 000 km²); dashed line represents area of secondary interest (29 000 km²).

This site was selected for several reasons. First, it is representative of the Sonoran desert region, which covers a vast area of the southwestern United States and Mexico and is being rapidly developed by man because of its pleasant climate. Secondly, the site is usually free of cloud cover and therefore has a high probability of being observed by the forthcoming ERTS-A sensors. Thirdly, a wealth of high-altitude aircraft and space photography of the area is already available for comparative analysis. And finally, much of this data has already demonstrated potential benefits that can accrue through the use of integrated multidisciplinary, multivariant, multistage, and multiband observation techniques.

Let me clearly define these last terms by a series of illustrations that will demonstrate how this approach ties together. Shown in the table is a list of some agencies presently involved in the ARETS experiment. These agencies include representatives from many scientific and other disciplines. Across the top is a list of the types of information that can be extracted from remote sensor data of various types. Most of this information can be extracted from photography taken at various wavelengths, and in this sense it is a multiband experiment. The major categories of information desired are (1) resource inventory, (2) land use, and (3) resource management. The X's indicate that some agencies work mainly in the inventory and land use areas; but a large number span the table, extending into the management area.

Large volumes of data have been collected over the Arizona area since 1965 from aircraft and spacecraft at various altitudes. Ground observations have also been made periodically in conjunction with the overflights. It is this use of observations taken from various altitudes and providing different scales and resolutions that we refer to as multistage sampling techniques. These are used to reduce the amount of total information required to inventory, classify, and manage an area. Repetitive observations taken during different seasons over a period of years have recorded changes in vegetation, urban expansion, and water and snow distribution. These we refer to as multivariant observations.

Studies of such data have included:

(1) Mapping the distribution of vegetation, both natural and cultivated (figures 2 and 3). These activities have been followed by studies of vegetation types and changes due to crop rotation.

(2) Mapping the distribution of snow and surface water in rivers, lakes, and irrigation areas (figure 4).

(3) Studies of manipulation of phreatophyte vegetation and changes in evapotranspiration and ground water levels as water-loving plants are removed from river valleys and these areas are converted to irrigated farmland (figure 5).

(4) Studies of rangeland and forest vegetation and their ecosystems.

(5) Investigations of Englemann spruce beetle infestations in one of the last major spruce stands of the United States.

(6) Measurements of mining activity and solid waste materials (figure 6).

(7) Studies of air pollution from industrial sources (figure 7).

(8) Mapping of soil associations and land use with photographs from several altitudes (figures 8 and 9).

(9) Identification of geologic anomalies as they may relate to mineral exploration.

Uses of remote sensor data in the Arizona Regional Ecological Test Site area

Agency \ Applications	Resource Inventory																		Resource Management								
											Land Use																
	Surface water	Snow	Ground water	Land subsidence	Soil/Bedrock	Arable lands	Vegetation—natural	Vegetation—cultivated	Geologic hazards	Mineral	Urban	Suburban	Rural	Recreation	Industrial	Agricultural	Transportation	Tourism	Environmental	Watershed; control of water	Irrigation control	Flood control	Land use planning	Timber production	Rangeland grazing	Industrial development	Farm crop production
Univ. of Arizona	X	X	X	X	X	X	X	X	X	X					X	X				X							
USGS/WRD	X	X	X	X			X													X	X	X					
USGS/GD				X	X			X	X						X				X								
USGS/Geog. Program	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X				
Bur. of Indian Affairs	X	X	X		X	X	X	X		X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Bureau of Land Mgmt.		X					X	X		X										X	X	X		X	X		
USDA/U. of Calif.							X	X				X	X			X								X	X		X
USDA/SCS					X		X	X					X			X					X						X
USDA/Univ. of Oregon							X												X						X		
Bur. Outdoor Rec.	X	X			X		X	X	X		X	X	X	X			X	X	X			X	X				
Bureau of Mines				X	X				X	X					X				X							X	
Ariz. Highway Dept.	X	X		X	X				X		X	X	X	X	X		X	X		X	X	X				X	
Ariz. Dept. of Property Valuation				X						X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	
Ariz. Dept. of Planning and Development	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

I wish to expand on this latter topic because it provides a case history on the very important subject of nonrenewable mineral resources.

During my studies of Apollo 9 photography (figure 10) I identified a circular topographic feature that was enhanced by the pattern of snow and shadow from a low Sun angle. The circle is 6.4 km in diameter and was not indicated on any of the geologic maps of the area. Only preliminary geologic mapping at a scale of 1:250 000 had been done in the area. After a brief field trip to the San Carlos Indian Reservation in eastern Arizona, I described the feature in a short memorandum. A review of available data was made, and our geophysicists discovered that it was underlain by a magnetic anomaly of about 200 gammas (figure 11).

FIGURE 2. Apollo 9 color IR photo of Phoenix area showing vegetation areas in red.

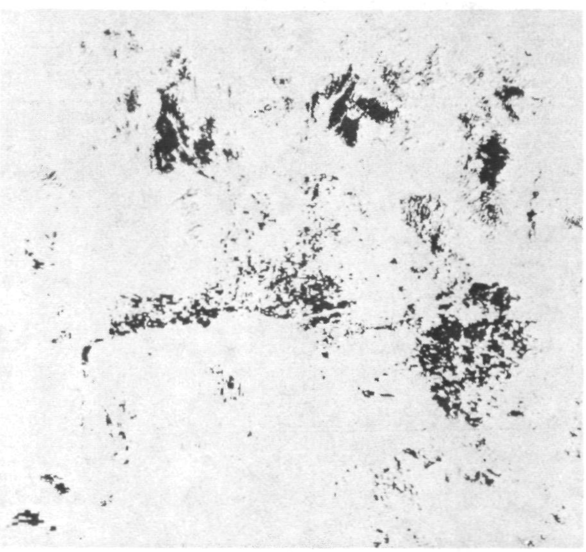


FIGURE 3. Vegetation map automatically extracted from space photography of figure 2.

Although this information was based on high-altitude, widely spaced data, the anomaly is similar in magnitude to other anomalies in the region, some of which are associated with copper ore deposits that have been known and mined for years. A plan was therefore developed to map the geology of the feature in detail, to conduct gravity and magnetic surveys on the ground, and to fly aeromagnetic surveys at a lower altitude and closer spacing. While these studies are not yet complete, we can say that the preliminary results are promising.

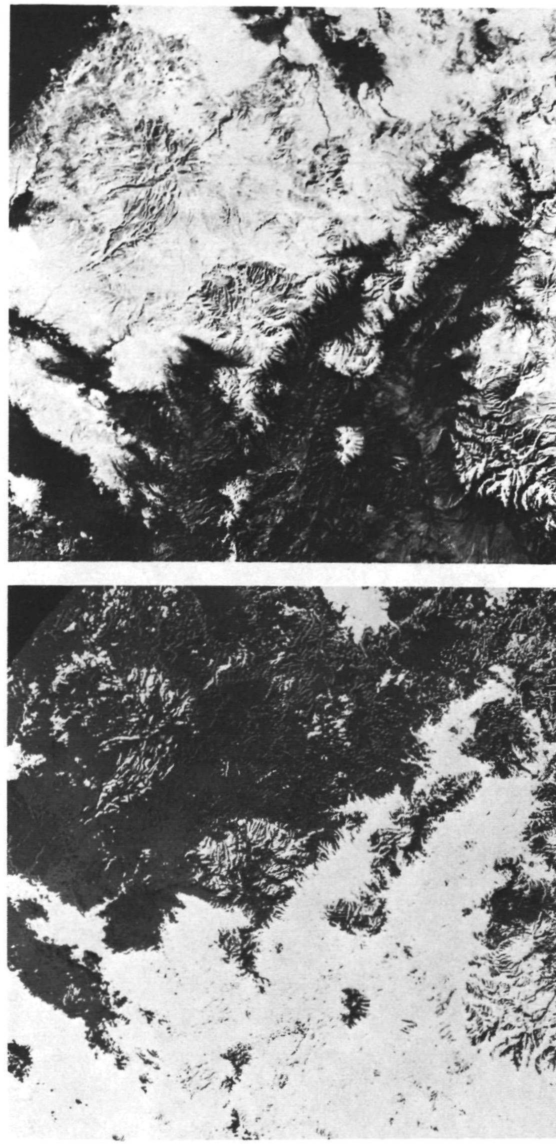
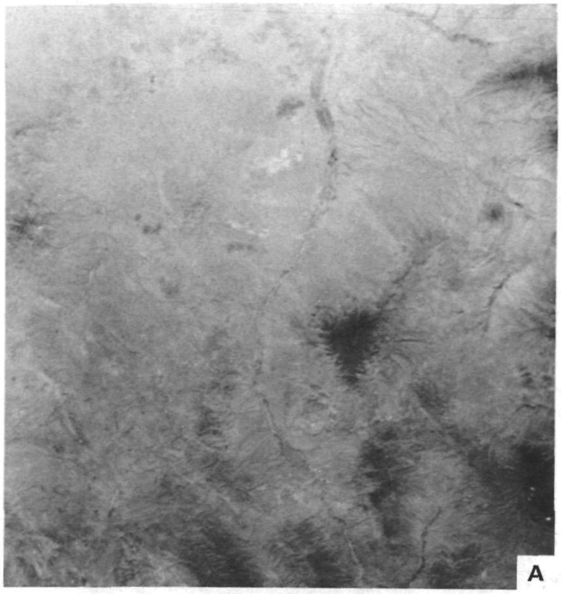


FIGURE 4. Automated snow mapping. Two-color map at bottom represents areas of thin and thick snow cover derived from color IR space photo at top.

The geologic mapping has shown that the circular feature is a structurally controlled block bounded by intersecting faults that interrupt the northwest-trending faults typical of the basin and



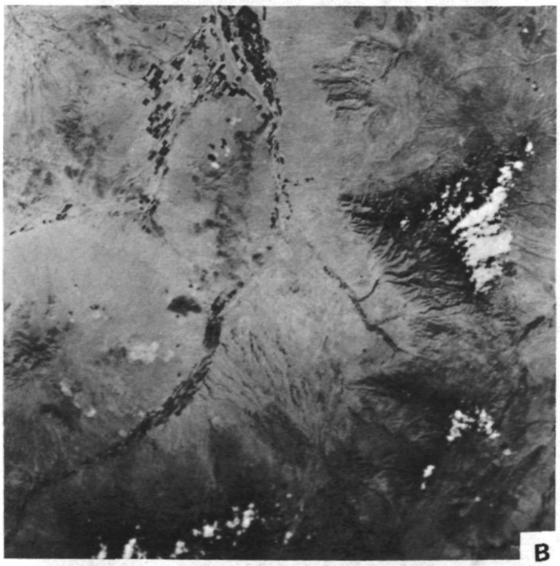
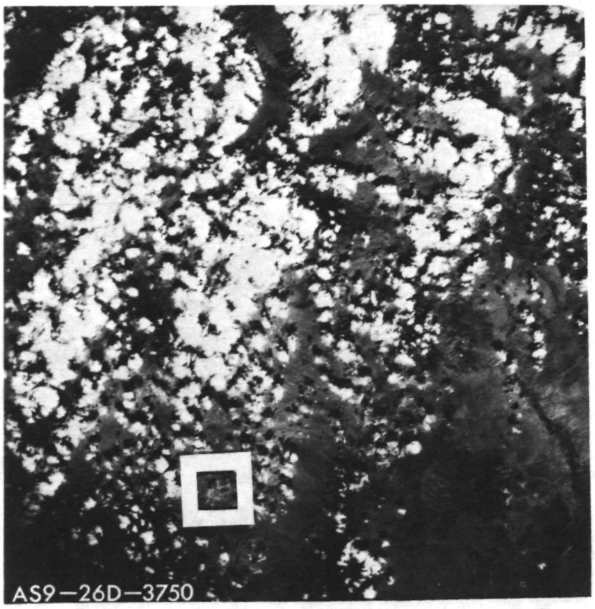


FIGURE 5. Three space photos of Tucson area showing differences in repeated observations (A, Gemini IV, 5 June 1965; B, Gemini V, 22 August 1965; C, Apollo 6, 4 April 1968).

range province. A gravity high, one of the largest in areal extent mapped to date in the State of Arizona, underlies the structure. The closely spaced, low-altitude aeromagnetic data remain to be completely analyzed. This combination of information, however, and the proximity to known copper deposits of economic value suggest that the area should be studied for more detailed information. Subsequent work has shown that the rocks in the area are too young to contain copper deposits of the porphyry type. Nevertheless, we are now conducting induced potential geophysical surveys in the area to confirm that there are none.

What sort of meaningful products do we hope to get from the Arizona Test Site experiment?

Because the Arizona experiment is still in its infancy, final products have not yet been defined. However, a recent study of the NASA Rocket Test Facility in southwestern Mississippi (figure 12) provides us with several models of the types of



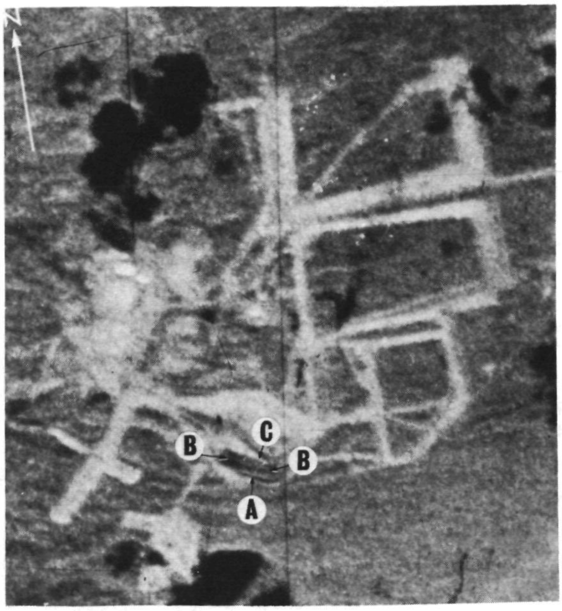


FIGURE 6. Copper mine details visible in enlargement (right) of small area of space photo (left). Letters indicate locations of mine benches.

FIGURE 7. Air pollution sources can be spotted from space. Here, mountain breezes carry smoke from the Hayden smelter down the Gila River Valley toward Phoenix.

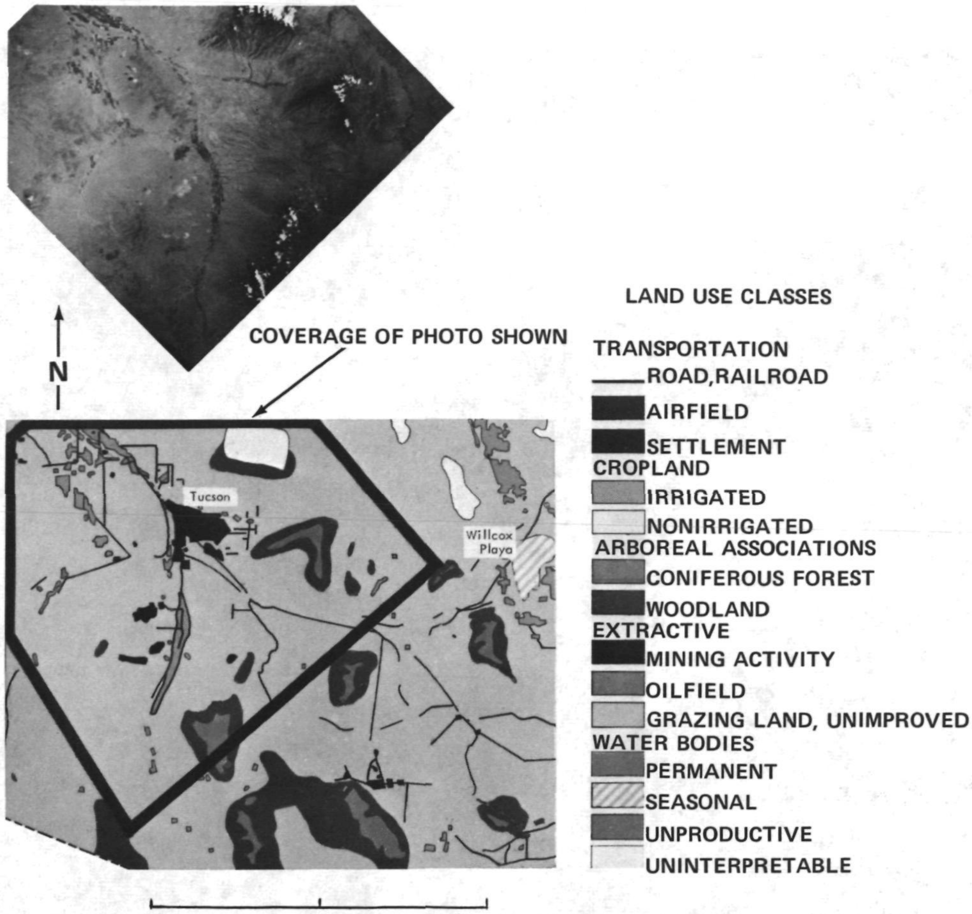


FIGURE 8. Regional land use classification from Gemini color photography.

information that we hope will be forthcoming. They include a semicontrolled mosaic of the area (figure 13) with transparent overlays or maps of equal scale depicting:

(a) *Cultural features*—urban, suburban, industrial, rural, parkland, highways, railroads, and airports.

(b) *Vegetation distribution*—cultivated, natural, forest, and rangeland.

(c) *Surface water distribution*—lakes, rivers, stock ponds, swamps, reservoirs, irrigation canals, and moist soil due to rain or irrigation.

(d) *Geologic features*—bedrock, alluvium, structural features, and distribution of known mineral resources.

As repetitive data become available, new maps will be made to depict changes in the above categories of information. These will then be available to serve as a basis for inventory records, land use evaluation, and planning.

In conclusion, may I say that my participation in the development of the Arizona Regional Ecological Test Site has been a gratifying experience. We have found that scientists from many disciplines and many diverse public agencies and universities within the State are eager to participate in this experiment. Our job now is to train the members of our team and to provide them with the data they need to evaluate the systems to be flown in the ERTS project. By a team approach, we hope to get a thorough evaluation of Earth resources data from space and attain the economic benefits that we believe can be provided by synoptic, multiband, multivariant observations from space platforms.

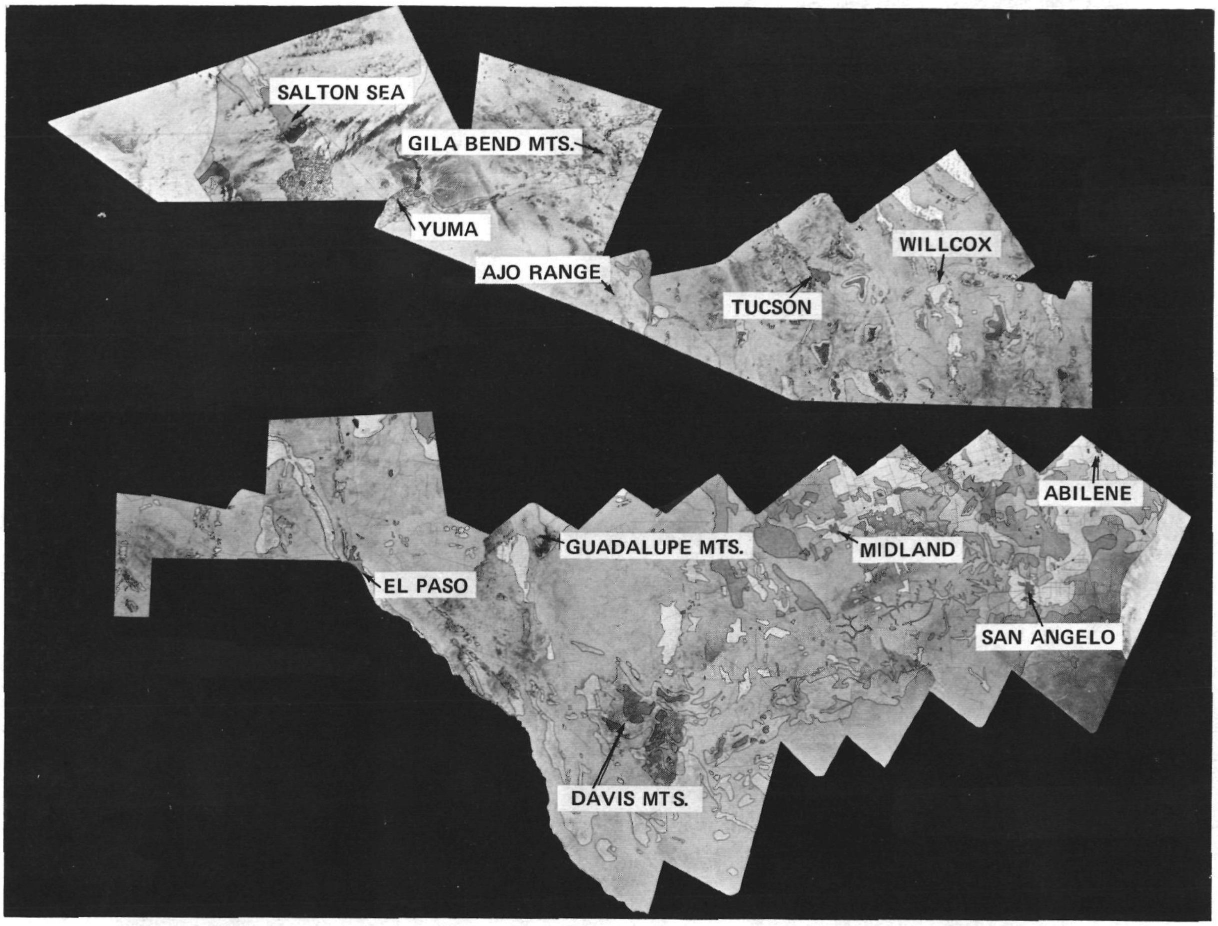


FIGURE 9. Land use maps of southwestern U.S. areas based on space photography.

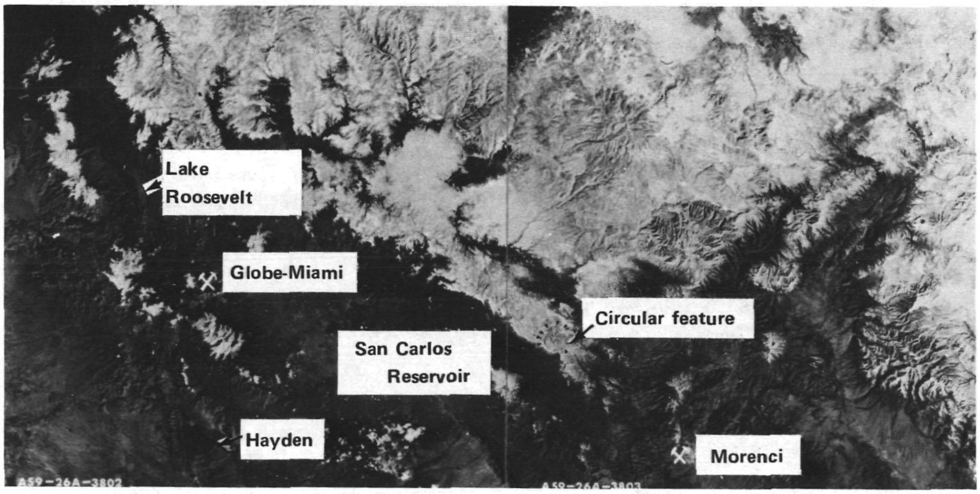


FIGURE 10. Space photography reveals mineral exploration target (circular feature) on San Carlos Indian Reservation, Arizona.

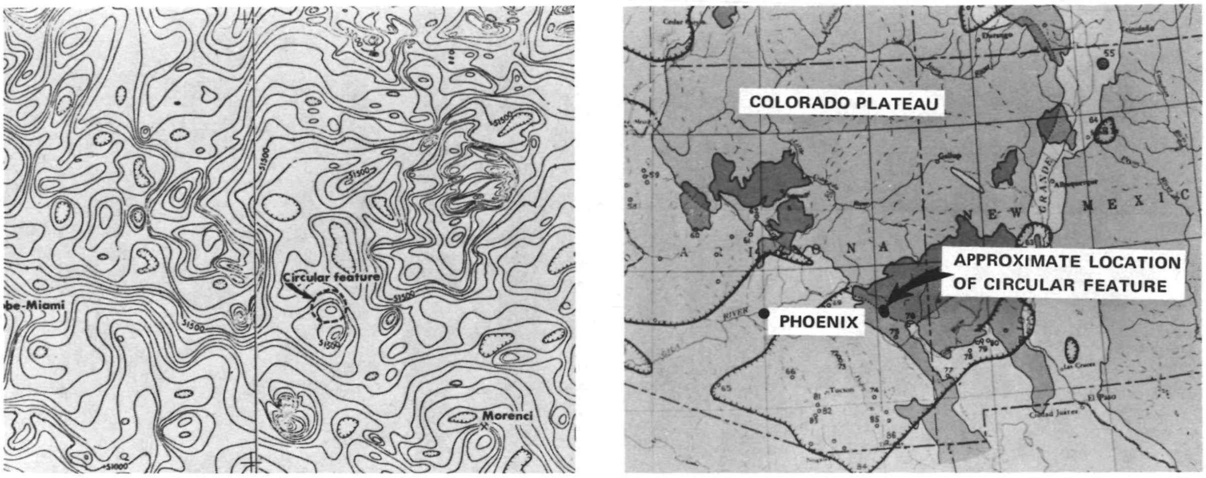


FIGURE 11. Correlative geologic data on circular feature (left, aeromagnetic survey map; right, metallic provinces map).

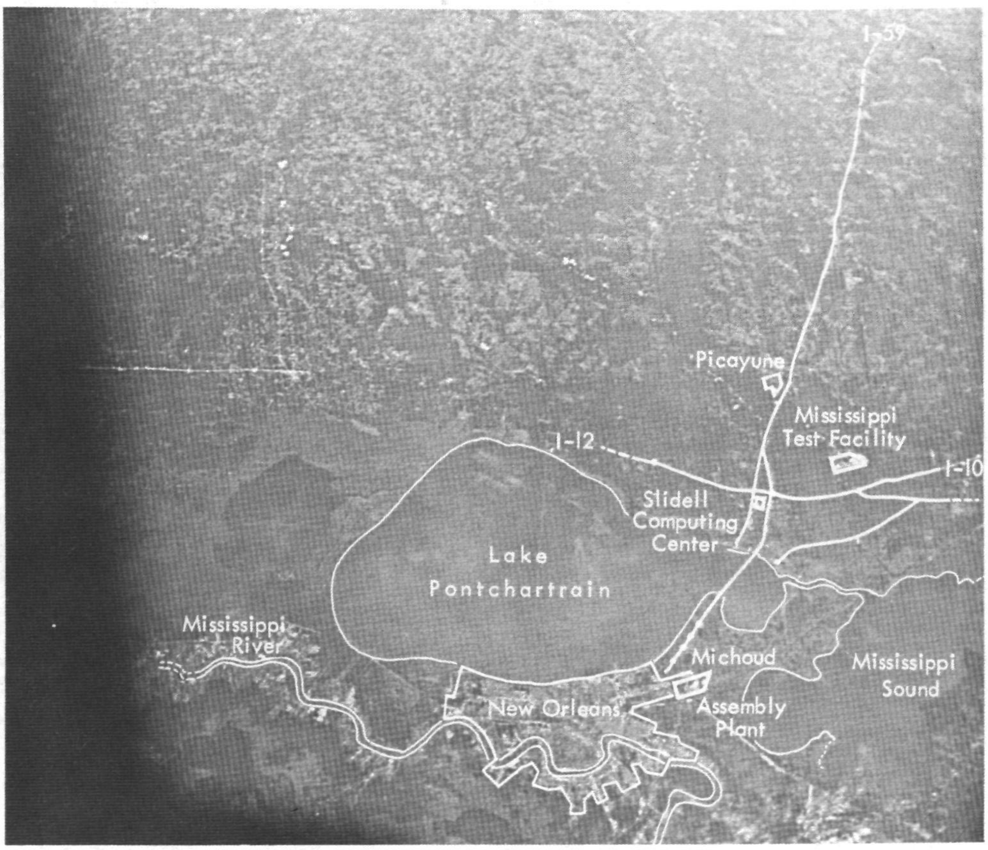


FIGURE 12. Apollo 7 photograph of Mississippi Test Facility area, 1968.

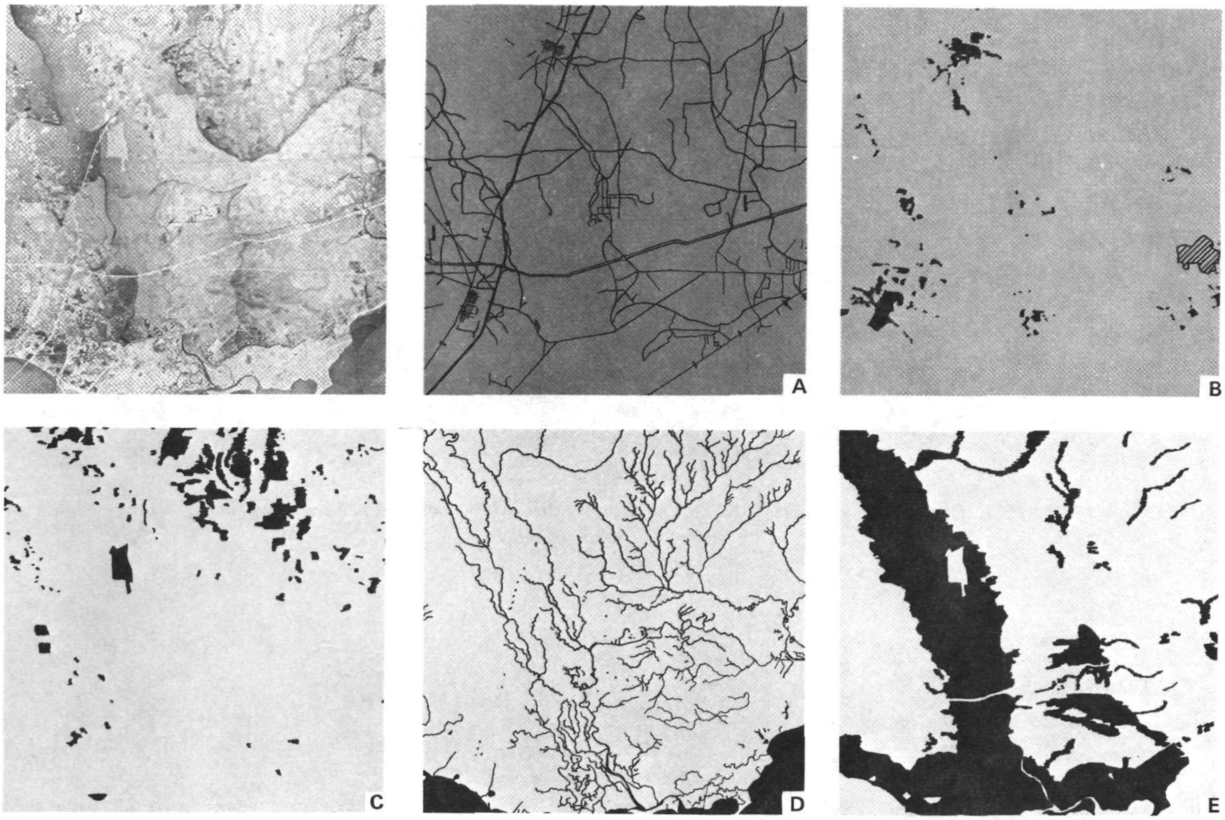


FIGURE 13. Aerial photo of Mississippi Test Facility area (1970) with corresponding maps depicting (A) transportation, (B) urban development, (C) agriculture, (D) water and drainage, and (E) lowland marsh areas.

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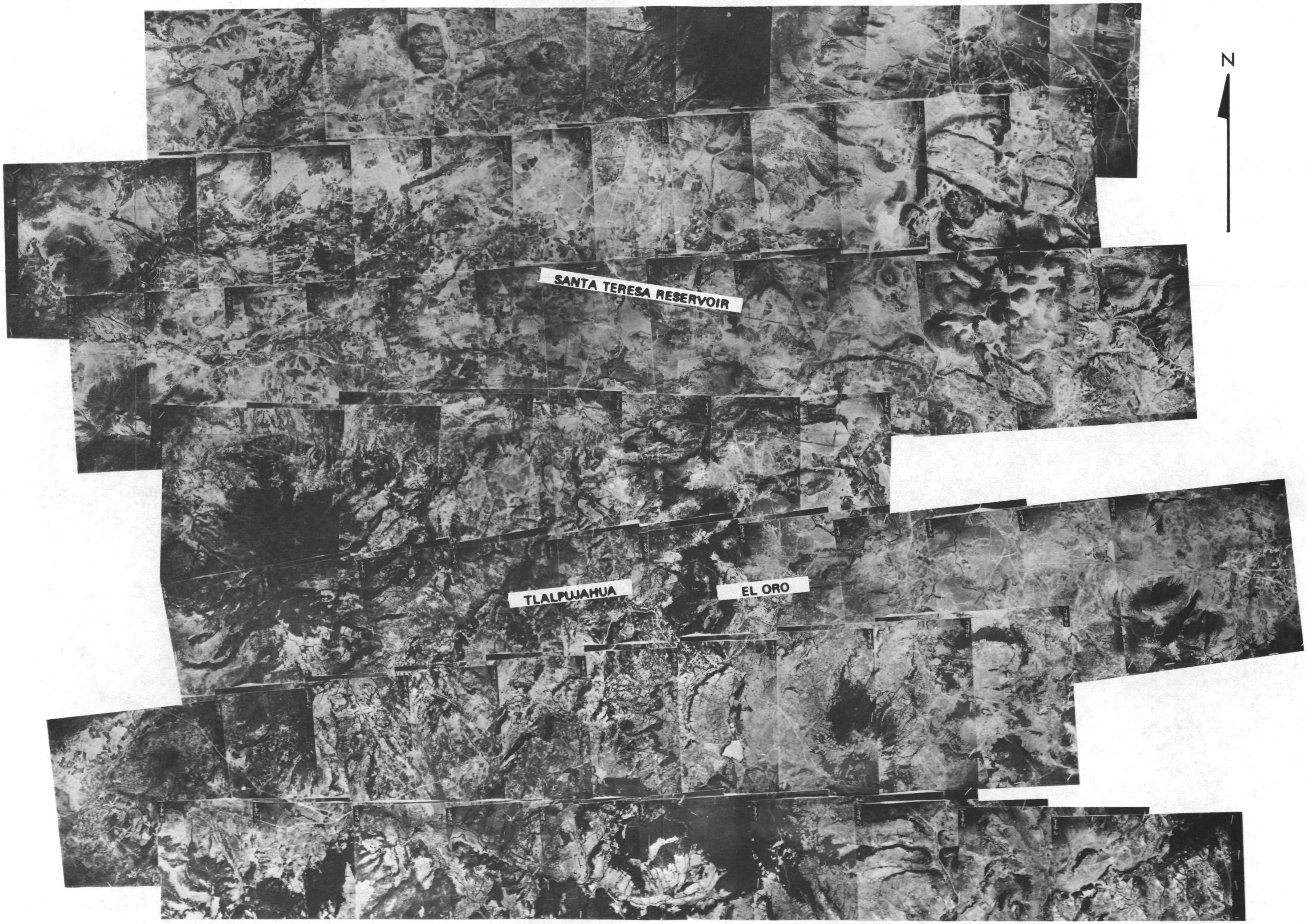

FIGURE 2. Photomosaic of test site area.

FIGURE 3. Photomosaic showing Atlacomulco-to-Maravatio section of new Mexico City-to-Morelia highway.

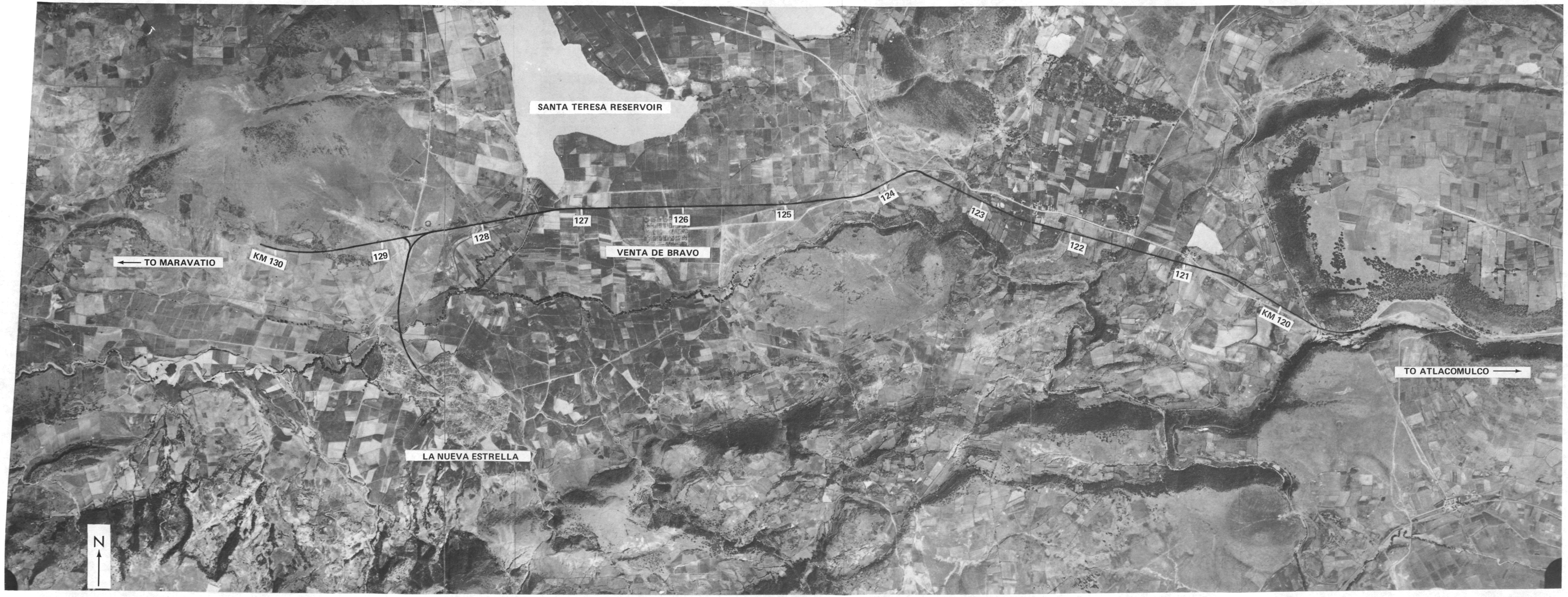

FIGURE 4. Aerial photo showing 10-kilometer section of new highway.

FIGURE 5. Identification of waterways and roadways.

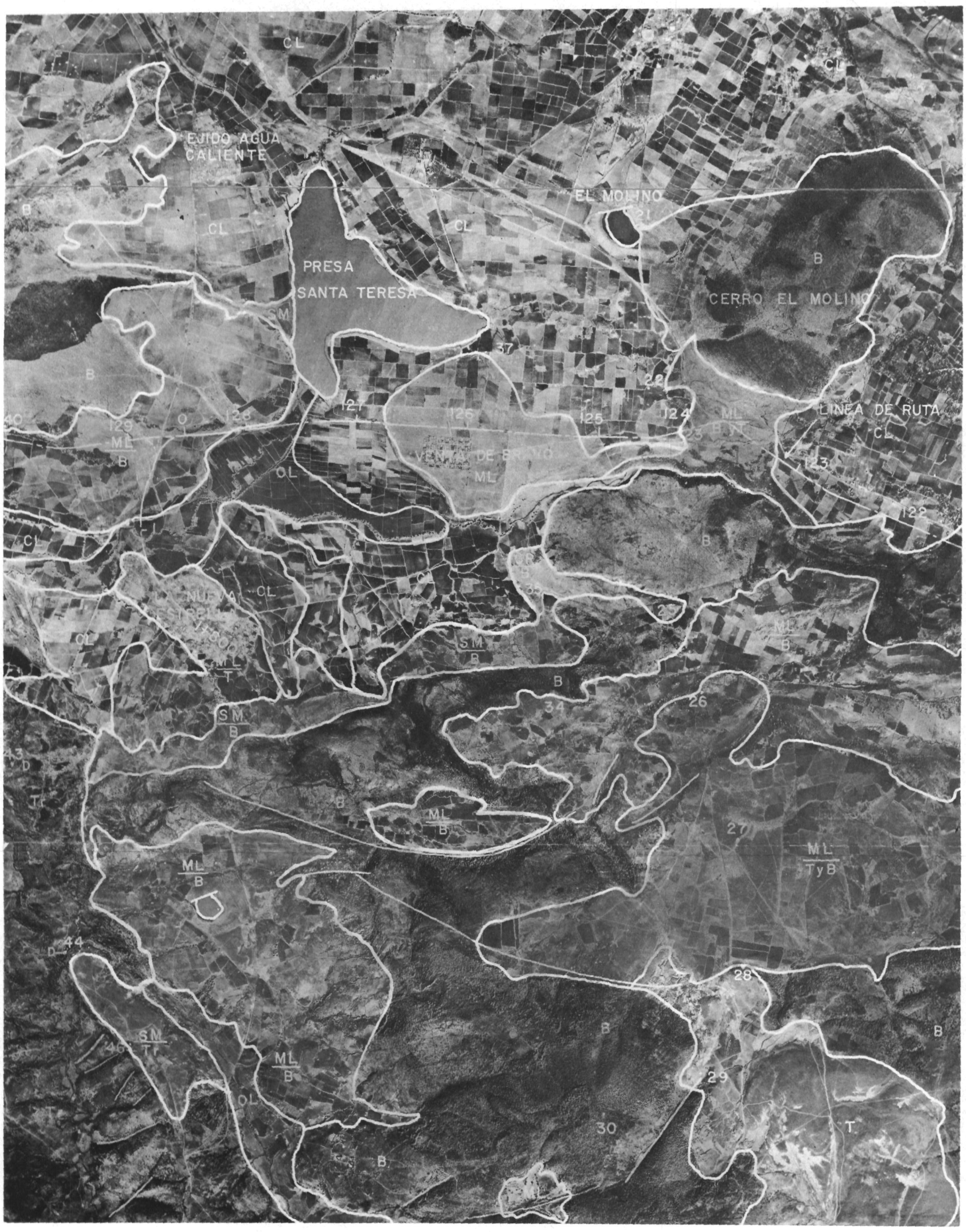

FIGURE 6. Identification of soil types and geologic features.

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